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Developed weather deck fire detection solutions and recommendations

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Abstract

Early fire detection on ro-ro ships can mitigate the loss of lives and cargo. However, the use of fire detection systems on weather decks is currently not required by regulations. The lack of a deckhead to mount traditional point smoke/heat detectors means that such detectors are not suitable for use on weather decks, but there are several optical technologies that can be used to detect fires on weather decks from a long distance. During the LASH FIRE project, the performance of available optical fire detection technologies was firstly investigated using laboratory experiments. Subsequently, operational evaluations were conducted on board a ro-ro ship for over a year, followed by fire experiments, making it possible to assess and demonstrate the performance of the different detection technologies on board. The present document discusses the developed fire detection solutions considered for weather decks and gives recommendations regarding the implementation of the solutions on weather decks.

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Content

1 Executive summary

The present document discusses the evaluations of fire detection technologies for their use on weather decks to provide quicker and more reliable fire detection. Firstly, the challenging weather deck conditions and how they will influence the different types of detectors are discussed, and then the identification of new and improved detection methods through laboratory and onboard evaluations are discussed, followed by recommendations for fire detection on weather decks. This is while the evaluations for fire detection in open and closed ro-ro decks are discussed in deliverable D09.2 [1], and the evaluations for fire confirmation and localisation are discussed in deliverable D09.3 [2].

1.1 Problem definition

Regulations currently do not require the use of any fire detection systems on weather decks, but this is soon expected to change. Moreover, the importance of fire detection and suppression on weather decks is evident in light of past major fire incidents on weather decks [3]. In this regard, early detection is expected to be especially important for being able to handle the fire with minimal damage. Compared to manual fire detection by fire rounds or observations from the bridge, the use of a suitable automatic fire detection system with good coverage over the full area of the weather deck is expected to provide significantly quicker detection in many cases. Accordingly, the goal of the current study was to find such detection systems that could enable early fire detection on the weather decks and handle the challenging weather conditions as well as the long distances involved.

1.2 Technical approach

Several systems capable of detecting heat, fire and smoke were tested for use on weather decks during the LASH FIRE project. The systems were first evaluated through laboratory experiments. Subsequently, installations were done on board an operational ship, namely, Hollandia Seaways (DFDS ro-ro cargo ship). The detection systems remained on board for over a year, and the nuisance alarms were recorded during normal operations. Lastly, several fire experiments were conducted to verify the residual detection capacity of the systems for identifying fires on board.

1.3 Results and achievements

An overview of the different relevant fire detection methods is presented as well as an overview of the different challenges that the detectors must overcome to reliably detect fires without too many false alarms.

Laboratory experiments were conducted with various detection systems as part of the LASH FIRE evaluations for fire detection, confirmation, and localisation [1], [2]. The present document discusses the laboratory experiments with flame wavelength detectors and thermal imaging (IR) cameras as part of two corresponding Risk Control Measures (RCMs) for weather deck fire detection solutions under Risk Control Option 10 (RCO10). The experimental results show that each detection technology can detect certain types of fires. Among the different manufacturers of the similar systems, the sensitivity settings and other algorithms used for evaluating and presenting the detected signals were found to play a clear role in the detection times, but the same types of fires were detected in principle.

Flame wavelength detectors were able to detect visible flames very quickly, although the size of the detectable fire depended primarily on the distance to the fire and the sensitivity settings of the detector. The reflections of flames were also found to be identifiable, i.e., without a direct line of sight between the flame and the detector.

Infrared thermal radiometry cameras or IR thermal cameras triggered alarms based on emitted infrared radiation from hot surfaces or gases. In cases where the fire was completely concealed, like inside a steel container, the thermal imaging cameras detected the increased surface temperature on the roof surface of the container. Alarms were also triggered by reflections of flames.

Following the laboratory experiments, installations were made on board a ro-ro ship for operational evaluations and fire testing, namely, on Hollandia Seaways (a DFDS ro-ro cargo ship). The weather deck installations included not only two thermal imaging detectors and three flame wavelength detectors (two IR3 and one IR array), but also a video flame detector and a hybrid detector (video fire detector + thermopile heat detector). Several experiments were also conducted on board the ship in the beginning and at the end of the operational trial.

After a year of operational evaluations, it was found that multi-spectrum IR flame wavelength detectors offered the most reliable results, as they did not have any nuisance alarms while they detected all the fire experiments consistently within seconds, both at the onset of the operational trial and at the end of the trial period.

1.4 Contribution to LASH FIRE objectives

This deliverable provides insights on the performance of different detection systems on weather decks and presents an overview of the possibilities and challenges for detection of fires on weather decks. Essentially, these detectors can provide quicker and more reliable fire detection on weather decks and aid in confirmation and localisation with live video transfer from the ongoing event to the operators on the bridge compared to only relying on manual observations without a fire detection system.

1.5 Exploitation and implementation

The evaluations presented in this deliverable show benefits and drawbacks associated with the different detection technologies, which is important information for manufacturers of the detection technologies, the suppliers, the installers, and the final users of the systems. The deliverable also demonstrates the complexities of evaluating the detectors and provides recommendations on how to test detectors and how to select a set of detectors for a specific environment. Finally, the demonstrations of commercially available fire detection systems show that the current regulations allowing weather decks to be unprotected should be reviewed.

2 List of symbols and abbreviations

AFV	Alternative fuel vehicle
BEV	Battery electric vehicles
CCTV	Closed circuit television (surveillance camera)
C-ITS	Cooperative intelligent transport systems
CLIA	Cruise Lines International Association
EV	Electric vehicles
FSS	Fire safety systems (international code)
FTP	fire test procedures (international code)
HGV	Heavy goods vehicle
HRR	Heat release rate
IACS	International Association of Classification Societies
IMO	International Maritime Organisation
IR	Infrared
kW	kilowatt
LOA	Length overall (of a vessel's hull measured parallel to the waterline)
MAIB	Marine Accident Investigation Branch in the UK
MSC	Maritime Safety Committee
N/A	Not activated
ND	Not detected
ONVIF	Open network video interface forum
OOW	Officer of the watch
RCM	Risk control measure
RCO	Risk control option
Ro-pax	Vessel type with both roll-on roll-off cargo and passengers
Ro-ro	Vessel type with cargo type roll-on roll-off
SOLAS	Safety of life at sea (international convention)
Tugmaster	The small vehicle that drives the trailers on/off board

3 Introduction

Main author of the chapter: Davood Zeinali, FRN

Regulations currently do not require the use of any fire detection systems on weather decks, but this is soon expected to change in light of past major fire incidents on weather decks [3] and due to technology developments which are expected to be adequately suitable for providing the required fire protection on weather decks. In this regard, a fire detection system that quickly identifies fires is considered crucial as it enables controlling the fire at an early stage before it grows too large and out of control.

The ideal fire detection system must be able to differentiate between an imminent fire and a normal situation. In other words, the detection system should not be so sensitive that it triggers too many nuisance alarms, and it must withstand the harsh weather conditions at sea with an acceptable level of maintenance requirements. Correspondingly, the goal of the current project was to find the types of fire detection system that could give the best overall solution for the quick detection of fires in the challenging conditions of the weather deck on a ro-ro ship.

In open and closed ro-ro decks, the deckhead causes the smoke and heat to accumulate, so they can be detected by point detectors of smoke and heat along the deckhead. On weather decks, however, the smoke and heat from the fire are dispersed naturally because of the open environment, wind, and the lack of a deckhead. Therefore, conventional point smoke and heat detectors cannot be used on weather decks.

As an alternative to point smoke and heat detectors, optical detectors can be mounted on the ship’s superstructures on the weather deck to provide coverage over a large area. As these detectors do not require a physical contact with smoke and convective heat from the fire, they are most effective for fire detection from a distance, which is essentially what is desired for weather deck fire detection. Accordingly, this document evaluates optical detection technologies that can be used on weather decks.

The evaluations discussed in this deliverable relate to the LASH FIRE work regarding fire detection on weather decks based on laboratory experiments and long-term testing on board a ro-ro ship during normal operations and finally fire tests on board, providing recommendations based on the results of the study. The work related to detection in open and closed ro-ro spaces is reported in deliverable D09.2 [1], and the evaluations for fire confirmation and localisation are discussed in deliverable D09.3 [2].

4 Weather deck conditions and requirements

Main author of the chapter: Sif Lundsvig, DFDS

A weather deck is defined by SOLAS II-2/3 as *"a deck which is completely exposed to the weather from above and from at least two sides."* This means that there is no deckhead above the vehicles. In terms of fire detection, this means that conventional point smoke and heat detectors cannot be used.

4.1 General requirements for detection systems

SOLAS II-2/20.4.1 [4] requires a fixed fire detection and fire alarm system to be fitted in all ro-ro spaces. However, as per the Unified Interpretation (UI) SC 73 of the International Association of Classification Societies (IACS) [5], it is widely accepted that no fixed fire detection and fire alarm systems are required on weather decks used for the carriage of vehicle with fuel in their tanks. This is while MSC.1/Circ.1615 [6] proposes to install a fire detection system on weather decks for new ships:

> "A fixed fire detection and fire alarm system should be provided for weather decks intended for the carriage of vehicles. The fixed fire detection system should be capable of rapidly detecting the onset of fire on the weather deck. The type of detectors, spacing, and location should be to the satisfaction of the Administration, taking into account the effects of weather, cargo obstruction and other relevant factors. Different settings may be used for specific operation sequences, such as during loading or unloading and during voyage, in order to reduce the false alarms."

However, it must be noted that MSC.1/Circ.1615 is merely a guideline and thus applicable only on a voluntary basis, focusing on passenger ships. In addition, no detailed technical standard is currently available to specify which kind of fire detection would be effective on weather decks and which kind of fire detection system could reasonably be installed on weather decks.

4.2 Operational conditions and requirements of detection systems

Fire detection on weather decks depends mainly on manual observations. This can be the Officer of the watch (OOW) looking out over the deck while navigating the ship, or it can be fire-rounds made by a deckhand or other crew seeing to the ship during workhours, or mandatory fire rounds for ro-ro ships with passengers (ro-pax vessels).

As long as manual inspection is the primary means of fire detection, it results in less attention paid to the aft weather deck, because the OOW watches over the foredeck as a natural part of their job, but not the aft deck. This also results in a non-systematic detection, which might lead to late detection. Moreover, only clearly visible signs of fire will alert the OOW and the crew, such that a small fire may go unnoticed until it grows large and potentially out of control.

Vessels often have CCTV surveying the weather deck, but this is not primarily for fire detection. Moreover, some vessels have thermal imaging cameras installed looking out over the weather deck. Due to the length of some weather decks, however, a single camera may not be able to monitor the entire deck effectively, especially if placed only on the available superstructure of the ship. Installation on poles or masts is possible, but access for required maintenance, vibrations, and safety from falling objects must be managed effectively. Such operational requirements are important in addition to the optimisation of detector locations for best area coverage.

For ro-ro ships, trailers can sometimes be placed so close together that access on the deck is limited in some areas. This can be a safety issue for manual inspections, but not for systematic fire detection. Densely stowed weather decks will also limit the visibility of a fire source. In very bad weather, the weather decks can be closed for access, thereby hindering manual inspections.

5 Cargo fires on ro-ro decks and weather decks

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Statistics suggest that 90% of the fires inside ro-ro decks originate from the cargo items themselves [7]. Cargo fires in open/closed ro-ro decks are discussed in detail through LASH FIRE deliverable D09.2 [1], and their origins are expected to be of a similar nature to those of weather decks [3].

There were 25 cargo fire incidents on operational ro-ro ships between 1990 and 2003, and 35 fires between 2005 and 2015 [3]. Between 2016 and September 2023, as listed in Table 1, there have been 12 cargo fires on operational ro-ro ships which were costly, i.e., excluding inconsequential fires and those that occurred after other major failures such as extreme listing.

Table 1: Consequential cargo fires on operational ro-ro ships between 2016 and September 2023 (excluding fires that occurred after other major failures such as extreme listing).

Time	**Ship**	**Cause, location, and consequences of the fire**
July 2023	Fremantle Highway, vehicles carrier	Unknown fire source in an upper deck, one casualty and 7 injured crew members, some oil spill and ship/cargo damage [8].
July 2023	Grande Costa D'Avorio, cargo ship	Unknown fire source in an upper deck, 2 casualties from firefighters, and 6 injured, some ship/cargo damage [9].
Feb 2022	Euroferry Olympia, passenger ship	A truck fire in the vehicles deck, 11 casualties, some ship/cargo damage [10].
Feb 2022	Felicity Ace, cargo ship	Unknown fire source in one of the cargo decks, capsized and sank with no casualties [11].
June 2020	MV Höegh Xiamen, vehicles carrier	Battery (12/24 V) in used/damaged vehicles not properly disconnected, with loose and unprotected cables and battery terminal posts, expected to have caused the fire in an upper deck as the ship was docked with a deactivated fire detection system after cargo loading, 9 firefighters injured, total constructive loss of the ship, and total loss of 2,420 used vehicles [12].
June 2019	MV Diamond Highway, vehicles carrier	Unknown fire source, total loss of cargo, and total constructive loss of the ship, caught fire again during salvage operations [13].
May 2019	Grande Europa, vehicles carrier	Two arson fires in the upper decks, one extinguished by the crew followed by another which was eventually extinguished by three firefighting ships, no casualties, some ship/cargo damage [14], [15]
May 2019	Platinum Ray, vehicles carrier	Unknown fire source in the upper decks, extinguished by the carbon dioxide fire suppression system of the ship with no casualties, 1 firefighter injury [16].
March 2019	Grande America, cargo ship	Cargo inside a container on the weather deck caught fire, the ship sank with weeks of oil spill, no casualties [17].
Dec 2018	Sincerity Ace, cargo ship	Unknown fire source in the upper decks, 5 casualties, some ship/cargo damage [18].
May 2018	Auto Banner, vehicles carrier	A vehicle engine fire on one of the upper decks while the ship was docked, total loss of cargo and the ship, no casualties [19].
Feb 2017	Honor, vehicles carrier	A fault in the starter motor solenoid in a personally owned vehicle in the upper vehicle deck, extinguished by the carbon dioxide fire suppression system of the ship with no casualties, 1 firefighter injury and extensive damages to the ship and its cargo [15].

Of the 12 cargo fires between 2016 and September 2023 listed in Table 1, only one incident was confirmed to be a weather deck fire, namely, the fire on cargo ship Grande America in March 2019. According to the final investigation report [20], the incident was due to cargo inside a container catching fire, i.e., a concealed fire which was detected by a deck officer in terms of white smoke and flames between two containers, one of which contained dangerous goods classified IMO9, i.e., miscellaneous dangerous goods and substances not falling under any other class [21].

In addition to the major fires mentioned above, two near miss incidents are notable, namely, a fire on the vehicles carrier Höegh Transporter in November 2020 originated in a vehicle after the completion of cargo operations, which was extinguished without further damage, and a fire on vehicles carrier Arc Independence in August 2020 which was detected by the ship’s detection system and contained to a single vehicle by the crew using fire extinguishers [15].

An investigation of 38 fires reported to the British Marine Accident Investigation Branch (MAIB) revealed that the most frequent fires on vehicle decks were due to electrical fires on refrigerator trucks known as reefer units or reefers [22].

Based on another analysis of fire causes [3], the shifting of cargo items on weather decks or open ro-ro decks are contributors to fire incidents on ro-ro ships, as well as the goods of vehicles which are undeclared or otherwise not normally stored, but the main contributors are suspected to be the electrical faults in the vehicles, their low voltage battery (typically 12 V), or charging means, especially reefers.

Special attention must also be paid to dangerous cargo or IMDG (International Maritime Dangerous Goods), leaking IMDG class 3 (flammable liquids such as petrol and diesel), flammable materials such as paint or oil, hot works and short circuits, old cars, and trucks with additional equipment connected in the driver’s cabin (such as heaters, kettles, or navigational equipment).

Any cargo items of fire concern are generally favoured for storage on weather decks [3]. IMDG items are only transported on weather decks, so these items are of particular importance when considering weather deck fire protection. Accordingly, checks are carried out on these units upon loading, and their corresponding paperwork are inspected to identify and follow their special transportation requirements, while proper segregation is also considered to minimise the fire hazard. Beside this, no other monitoring is currently done for IMDG cargo on ro-ro vessels.

5.1 Combustible materials on board

The main combustible materials on weather decks are those of vehicles, including their motor fuel or source of power, as well as their cargo, especially the cargo of trucks and trailers that can represent a large amount of combustible material.

Vehicles are primarily powered by either petrol or diesel at present. Alternative power sources, which may be more ubiquitous in the future, currently include batteries, liquified or compressed methane or hydrogen, as well as liquified propane and ethanol [23], [24]. These power sources have different characteristics, so each behaves differently in a fire as explained in LASH FIRE deliverable D09.2 for open and closed ro-ro decks [1].

Heavy Goods Vehicles (HGVs) or trucks, i.e., freight vehicles of more than 3.5 tonnes, are designed with larger fuel tanks and more combustible materials than regular passenger vehicles, e.g., because of their bigger tires, cargo hold cover, etc. However, the most significant difference of HGVs compared to smaller vehicles comes from their significant amount of cargo. Each truck may contain several tonnes of combustible material in solid, liquid or gas state. The combustible material in trucks may be classified as dangerous goods but may also be any other combustible material. The dangerous goods are declared at loading and placed with the proper segregation according to the category of the cargo.

5.2 Fire sources

Vehicles in a poor condition pose fire risks due to their potential electrical faults, battery problems, and leakage of fluids. Used cars are assumed to be in a poorer condition if damaged to the extent that they cannot be rolled onto the ship by their own power, but all used vehicles require a thorough inspection of their condition. The diverse cargo of the vehicles can also contain ignition sources, e.g., cooking appliances in camper vans or loose batteries stored improperly that could initiate or contribute to a fire in the event of a fault or external source of heat. Moreover, when the vehicles are loaded, they can have hot engines, exhausts, and brakes, which are sources of heat. However, these parts will normally cool down to ambient temperature soon after the vehicles are switched off.

Reefer units are connected to the ship’s power supply to maintain refrigeration without relying on the motor engine power during the ship’s voyage, and they are commonly placed in open decks or on weather decks. Short circuits or other faults in the related connections and units are known to represent a fire hazard on board [3]. Moreover, in cases where there are too many reefer units on board such that the number of charging points is not sufficient, some units may be allowed to have their engine running in an idle mode during the voyage. Such units will therefore maintain a hot engine, which could be considered a potential fire hazard.

Electric Vehicles (EVs) are not charged on board as a common practice today. Only 4 cases of fires in charging EVs were found globally in a recent survey of car park fires [25]. Three of these fires started while charging at high power and the fourth fire started in an extension cord. It is expected that ignition is more likely linked with higher charging currents. Accordingly, to charge several EVs simultaneously, the ship needs to regulate the charging current appropriately to be able to distribute the available power to the connected vehicles safely and efficiently. If the duration of the voyage is long, the charging power can be relatively low to make the charging process safer. Moreover, the charging process can be made safer if the battery capacity, state of charge, and desired power of each vehicle can be communicated automatically to the charging system [25].

6 Detection technologies

Main author of the chapter: Reidar Stølen, FRN

Table 2 shows an overview of available detector types that were reviewed in the LASH FIRE project. As the weather deck does not have any deckhead, there is no structure on which to mount detectors directly above the vehicles. Furthermore, smoke will also not accumulate and concentrate above the vehicles as in open and closed ro-ro decks. Therefore, detection systems that rely on sensor positioning directly above the fire, like point smoke and heat detectors, linear heat detection, and aspirating smoke detection are intrinsically unusable for weather decks.

Table 2: Overview of different smoke and fire detection principles.

Type of detector	Measurement parameter	Covered area	System architecture	Feasible for weather deck
Flame wavelength detection	Emitted IR and/or UV radiation from flames	Field of view of sensor	Sensors detect energy signature from an open flame in the full field of view. Array detectors use sensor array to locate the flame within the field of view.	Yes, with detection spectrum suitable for outdoor use.
Infrared thermal imaging cameras	Emitted thermal radiation	Field of view of camera	Local or centralised processing at camera.	Yes
Video detection of smoke	Visual characteristics of smoke	Field of view of camera	Raw video signals processed and analysed by software in a central server or onboard camera analytics.	Yes, if the detection algorithms can reliably detect smoke signatures in changing outdoor light conditions.
Video detection of flame	Visual characteristics of smoke	Field of view of camera	Raw video signals processed and analysed by software in a central server or onboard camera analytics.	Yes, if the detection algorithms reliably can detect flame signatures in changing outdoor light conditions.
Light beam linear smoke detection	Attenuated infrared light absorbed/reflected by smoke along the light beam.	Straight line of light beam. Up to about 100 m.	Alarm is caused by smoke obscuring light beam at a specific obscuration percentage. The detector consists of a transmitter and a receiver.	Not recommended for weather decks due to environmental factors.
Acoustic detection	Characteristic sound from a fire	Depends on background noise and type of fire.	Requires signal processing and analyses of the sound.	No systems were commercially available.

Point detectors	Smoke particles, temperature, gas	Measures single point	Sensors, data processing and communication in each unit.	Not usable for weather decks due to the lack of a deckhead.
Linear heat detection	Temperature	Along a cable. Up to several km length.	Central detection unit monitors temperature along sensor cable.	Not practical for weather decks due to the lack of a deckhead or a proper place near the floor.
Aspirating smoke detection	Smoke particles and/or gases	Ceiling of monitored area.	Air drawn through a network of pipes with small holes and sampled by a central detector.	Not usable for weather decks due to the lack of a deckhead.

As the weather deck is exposed to severe weather conditions at sea, the detectors need to be able to withstand these conditions and function without the need for frequent maintenance like lens cleaning, etc. The detectors that require line of sight to the fire source will require careful planning of location and direction to optimise the detector coverage. The best overview of the deck will in most cases be obtained from a detector position high above the top of the vehicles and cargo. Such elevated mounting positions on the perimeter of the deck can give a good overview of the weather deck. This gives an advantage to detectors that can monitor large spaces with a wide field of view. Nevertheless, the small space between the vehicles makes it difficult to obtain line of sight from fire sources located close to the deck, in between or below vehicles. The fire signatures may reach the detectors through reflections, or directly as the heat and flames rise towards the top of the cargo and vehicles. This means that the detection of the fire may be delayed until the fire has reached above the top of the vehicles and enters the field of view of a detector.

6.1 Reviewed detection methods

Optical detectors (referring in this document only to detectors that can view/see the fire from a distance, such as thermal imaging cameras) do not need to be placed near the fire, smoke, or elevated gas temperatures to be able to respond quickly. This allows optical detectors to cover large areas, which is essential for the effective coverage of a weather deck. Most optical detectors rely on infrared (IR) or ultraviolet (UV) light emitted from the fire source. For example, thermal cameras use infrared radiation to measure high temperature regions. Triple-IR flame wavelength detectors look at three thresholds of IR radiation and can identify flames from a long distance. Visible light is also used by detection systems such as video analytics algorithms that can recognise the visual characteristics of smoke or flame, e.g., colour, size, shape, flicker pattern, motion, and transparency.

Optical attenuation from smoke particles is also used as a detection principle in point smoke detectors, but these are categorised as point smoke detectors as they cannot detect optical fire signatures from a distance and will not be further evaluated for use on weather decks.

The different types of optical fire detectors that went through the LASH FIRE experimental and operational evaluations are flame wavelength detectors, infrared thermal imaging cameras, video fire analytics, and hybrid detectors combining heat and video detection. The working principle of light beam smoke detection and acoustic detection was reviewed, but these types of detector systems were not available for experimental and operational evaluations.

6.1.1 Flame wavelength detectors

The term “*flame detector*” [26] is classically used exclusively for detectors that have sensors for detecting IR or UV light expected of flame radiation wavelengths commonly associated with combustion products such as carbon dioxide. Such detectors are not to be confused with other flame detection sensors that employ different technology such as video flame detection relying solely on visible light. Accordingly, to avoid confusions hereafter, the present document refers to classic flame detectors as “*flame wavelength detectors*,” and especially uses it to focus on multi-spectrum IR flame detectors which have long-range detection capability suitable for ro-ro spaces (up to ~60 m for a 0.3 cm x 0.3 cm heptane fire), as opposed to UV/IR detectors which have short-range detection capability (up to ~30 m for a 0.3 cm x 0.3 cm heptane fire) and less immunity to nuisance alarms (e.g., due to arc welding, halogen lamps, metal grinding, and lightning).

The characteristic wavelengths emitted by hot CO_2 can be used to differentiate between flames and other nuisance sources like sunlight or hot surfaces. This is precisely what is done by flame wavelength detectors. These detectors have been used on offshore oil and gas platforms for several years where they have proved to be reliable in a maritime environment. Nuisance alarms from flame wavelength detectors in offshore oil platforms are commonly caused by the flare stack directly in the view of the detector or via reflections, but the relocation of detectors, and shielding or matting down shiny surfaces can reduce the number of such nuisance alarms in most situations.

Flame wavelength detectors have a detection range and field of view which can be visualised using a 3D cone as illustrated in Figure 1. Detailed guidelines for the placement of flame wavelength detectors based on their effective detection range can be found in the British standard BS 60080 [27].

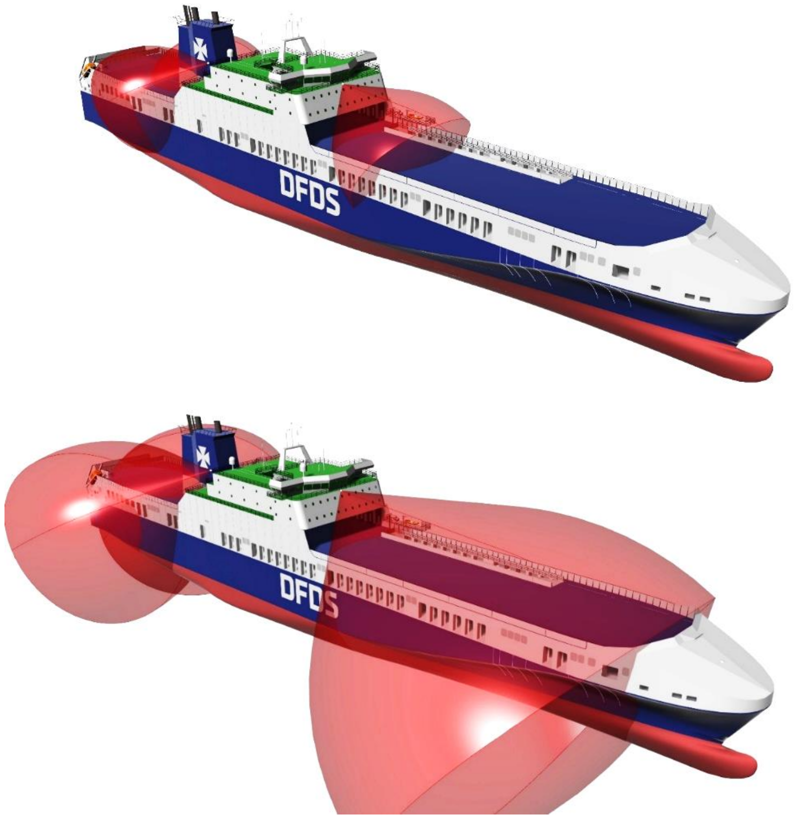


Figure 1: Example flame detector coverage visualisations for Magnolia Seaways (DFDS cargo ship). The top figure shows a coverage distance of 30 m (standard detection for a 0.1 m^2 heptane pan fire), while the bottom figure shows a coverage distance of 55 m aft of the superstructure and 85 m forward of the superstructure for the case of a larger fire source or with the use of a higher sensitivity setting by the detector. The detectors are mounted ~10 m above the weather deck.

Triple-IR (IR3) flame wavelength detectors can identify flames and their reflections by monitoring the ratios of infrared energy for three wavelength ranges which are specific to flames, particularly in the vicinity of 4.4 µm in the electromagnetic spectrum.

IR array flame wavelength detectors have an array of infrared sensors, and may use video analytics, that can locate and highlight one or multiple flames within the field of view. Like ordinary IR3 flame wavelength detectors, IR array detectors perform multi-spectrum (IR3) wavelength monitoring to identify flames.

6.1.2 Thermal imaging (IR) cameras

IR thermal cameras detect the heat that is transmitted from all objects in the form of infrared electromagnetic waves. These infrared waves are collected by the camera through optics and then focused on a sensor with pixels. The intensity of the infrared waves depends on the temperature of the object emitting the waves. This information from all the pixels in the camera can be put together as an image representing the temperature of the objects in its field of view in a similar way as a traditional camera can generate images of the visible light and colours of objects. The temperatures of the different pixels are colour coded in a visual image such that each colour represent a temperature. This allows temperature gradients and hot spots to be visualised in an image or a video stream.

The recorded thermal images can be processed and monitored by software that can trigger an alarm based on a maximum surface temperature criterion or more advanced algorithms including division into different zones covering different parts of the image. Masking certain areas with known hot objects can eliminate the nuisance alarms generated by these areas. Therefore, a proper commissioning of a thermal imaging detection system can consider the nuisance thermal signatures that are expected in normal operation and adapt the sensitivity settings and masking areas accordingly.

As the IR thermal cameras are sensitive to hot surfaces, they can detect areas that are hotter than other surfaces nearby. This can be used to detect potential ignition sources before any flame or smoke is released. This effect can cause nuisance alarms if the hot surface is not representing a fire hazard, or it can provide detection of an imminent fire at a very early stage before ignition.

6.1.3 Video fire detection

Video flame detection (VFD) and video smoke detection (VSD) are two types of video fire detection methods which use video analytics on regular camera footage to detect flames and smoke, respectively.

The footage used for video fire analytics can be from an already existing surveillance camera system (CCTV) which is analysed using the analytics software on a computer connected to the CCTV system. Alternatively, dedicated detectors are available that combine a video camera and the analytics software which can perform video fire detection without the need for a separate computer.

Video fire analytics algorithms process the video footage and look for patterns that are characteristic for fire and smoke. For the detection to work properly, it is usually expected for the light conditions to be stable, so the technology is considered evidently useful for closed ro-ro spaces. Nevertheless, it is not considered impossible to compensate for changing light conditions and avoid nuisance alarms on weather decks [28], [29], especially as the analytics algorithms improve over time and better ones continue to be developed.

6.1.4 Light beam smoke detection

Optical linear smoke detection is based on a ray of light being transmitted through the air across the desired protection area, and the attenuation of the light that reaches a receiver indicates whether there is smoke in the space. The transmitter and receiver are often located in the same unit, where the light is reflected in a reflector located at the opposite side of the protected space. This technology can be used to detect smoke across long distances. However, a careful alignment between the transmitter, receiver, and reflector is required for the ray of light to reach the receiver correctly.

For weather deck fire detection, this type of detector system is considered not practical due to ship vibrations and deformations which lead to challenges for the accurate alignment of the light beam. Moreover, weather elements and other obstructions are expected to trigger frequent nuisance alarms from this system. As a result, light beam smoke detection was not evaluated during the LASH FIRE project.

6.1.5 Acoustic detection

Acoustic detection is based on analysing the characteristic sound that is emitted from a fire. Different materials in a fire will emit characteristic sounds that can be detected by sound sensors. As the sound can be transmitted both through open air and through solid materials, the fires can be detected even without direct line of sight from the detector. Experiments have been reported to give early detection of fires in a small room with low ambient noise [30].

In a ro-ro ship, the ambient noise from other sources will most likely be a major challenge for acoustic detection systems, such that it is not expected for such systems to be able to detect a small fire at an early stage on board a ro-ro ship with a large variation in the potential fire sources. No available commercial products were found during the LASH FIRE project, making the technology difficult to assess for ro-ro ships. Moreover, no recent research on the topic was found, indicating that this principle of fire detection is still not mature enough for ro-ro ship applications. As a result, acoustic fire detection was not evaluated during the LASH FIRE project.

6.2 Alarm criteria

Different detection settings and criteria can be set for the detection systems for alarm generation. This includes a form of processing and analysis of data measured by the detection sensors, and the main goal is to separate fire scenarios from normal situations.

Normal situations can include many different scenarios and conditions, and the fire alarm criteria of detection systems must account for this. For instance, it would be quite normal to observe clouds of exhaust when vehicles are running during loading and unloading, but small streams of smoke from a vehicle during the journey must be interpreted as a potential fire. Similarly, high temperatures may be expected in vehicles as they drive onto the ship, but increasing temperatures after the vehicles have been parked in place must be interpreted as a potential fire risk.

Simple mathematic criteria can be defined for triggering alarms based on sensor data from temperature sensors, such as the examples presented in Table 3.

Table 3. Alarm criteria principles

Temperature measurement	**Example**
Given maximum temperature	>60 °C
Time above maximum defined temperature	10 seconds above 60 °C.
Temperature rate of rise	>10 °C increase in 1 minute
Temperature difference	>40 °C above ambient average

For video detection systems, the alarm criteria of analytics algorithms are usually complex as they should be able to recognise a flame or smoke in a complicated video stream. This makes it challenging to assess the functionality of these systems because the algorithms cannot easily be standardised or reviewed [31].

Thermal imaging can be used by simply triggering an alarm above a certain detected temperature or rate of temperature rise, but the image data may also be analysed further by using different detection zones, tracking the temperature over time and space, or comparing the temperature in one point with other points, and so on.

Analytics algorithms may also be used to highlight the location of the flames/smoke in the video (thermal or regular) footage to help with fire localisation and confirmation as discussed in LASH FIRE deliverable D09.3 [2].

6.3 Previous studies

The FIRESAFE II project studied detection systems in open ro-ro spaces and weather decks [32]. The report includes the evaluation of several different detection systems for weather decks. The evaluated detection methods are listed in Table 4.

Table 4. Detection systems evaluated in FIRESAFE II

Type of detector	**Potentially suitable for weather decks?**
Fibre-optic linear heat detection	No
Aspirating smoke detection	No
Gas detection with ASD	No
Video detection of smoke/flame	Yes
Video detection thermal, IR	Yes
Flame wavelength detection	Yes
Light beam linear smoke detection	If hull deflection can be accounted for
Acoustic detection	No available systems known

Based on an initial evaluation and cost-effectiveness assessment, an infrared thermal imaging camera system was tested on the weather deck on board the Stena Scandinavica. It detected a fire in clear sight immediately. A fire that was hidden behind a container was detected from the heat reflections on surrounding surfaces. Heavy rain (simulated using a fire monitor) delayed the detection time, as the water droplets in the air absorbed some of the radiation. The detection systems were left on board for 1 month after the fire tests to gather information on nuisance alarms. During loading and off-loading of the deck, there were several hundred nuisance alarms caused by the exhaust fumes and hot surfaces on the exhaust pipes of vehicles moving the cargo.

6.4 Challenges for detection on weather decks

6.4.1 Visual obscuration

In a tightly packed ro-ro deck, the spaces between the vehicles will be difficult to cover completely with optical detectors. On weather decks, the coverage with optical detectors will improve if the sensors are placed higher and can look down on the vehicles. In contrast, if a detector is placed relatively low compared to the height of the vehicles, the closest vehicle may block most of the field of view of the detector.

6.4.2 Light

Video smoke detection requires a certain ambient light to be able to see the smoke. Moreover, the contrast between the smoke and the background objects will influence how well the smoke can be detected by these systems. Video flame detection methods use only the visible light spectrum and need to differentiate a flame from other types of light by using video analytics algorithms. This is because unhazardous light sources may also exhibit some characteristics which are like those of a fire. For example, direct sunlight or that reflected from the sea surface or other moving surfaces may look like the flickering light from a flame.

Sensors that detect the IR or UV radiation emitted from the flames do not require any ambient light. For instance, thermal imaging cameras detect IR radiation and thus they can indicate any abnormal temperature increases caused potentially by a fire, but they would require a heated surface or its reflection that is visible to the thermal camera. The reflection may come from any surfaces which are specular (mirror-like) reflectors, e.g., a shiny metal surface.

Direct light from the sun or other powerful light sources may dazzle or blind optical detectors (e.g., due to overexposing the sensor or causing flaring and reduced contrast) or cause them to trigger nuisance alarms. This problem applies to almost all optical detectors. Accordingly, dazzling tests and certifications are included in some standards, e.g., see annex D in EN 54-10 [26].

Smouldering fires (i.e., fires without flaming combustion) will not emit visible light, and they often produce limited amounts of smoke in the early stages. These fires can be difficult to detect based on visible light, if not impossible. Using IR radiation, however, such fires can be detected more easily, e.g., using a thermal imaging camera with a field of view to the smouldering area.

6.4.3 Distance of fire to detector

In clear weather, the optical detectors may see the fire, smoke, or heat from great distances as the radiation travels through the air with very little attenuation. The size of the fire and the sensitivity of the detector will determine the effective distance of the detector in clear weather. If the air between the fire and detector is filled with rain, snow, fog, suspended particles, or solid objects that block the radiation from the fire, the effective distance of the detector will be reduced. The different wavelengths that each type of sensor uses are absorbed differently by molecules and particles in the air. For instance, water droplets can block infrared light or thermal radiation very effectively [33].

Tests conducted with two different video flame detection systems show that the detection time increases with distance for a given fire source [31]. This is because the flame appears smaller at longer distances, so the used video analytics algorithms need more time and data from the images before they can identify the flame.

When flame wavelength detectors are tested and classified, they are certified for a certain flame size and distance in a controlled environment [26]. In challenging conditions, such as rain, snow or fog, the fire must be closer or larger before an alarm is triggered.

6.4.4 Limited structures for fixing the detectors

The lack of any structure directly above the weather deck limits the possible mounting positions of the detectors to the perimeter of the deck. Different ships will have different possible mounting positions to look out over the weather deck. The superstructure of the ship and other solid structures with an overview of the weather deck can be used.

Optimal mounting positions will need to be assessed on each ship to allow the best possible coverage of the weather deck without too large blind spots. Additionally, the operational requirements discussed in section 4.2 need to be considered.

6.4.5 Wind

The weather deck will be exposed to both the ambient wind conditions and the apparent wind due to a ship's speed. Even though the weather deck is completely exposed from above, the sides may be partially shielded.

The wind will influence both the spread of fire and the way the smoke moves. The wind may also dilute the smoke in the early stages of a fire, making it less visible to optical sensors.

Tarpaulins on vehicles may also start moving and fluttering in the wind. For video analytics, this may be interpreted as moving smoke or even flame if sunlight is reflected (when the tarp is wet or glossy).

6.4.6 Rain, snow, frost, ice, and sea salt

As the rain and snow fall mostly from above, weather decks are the main areas exposed to these weather elements. Such elements in the air between a fire and an optical sensor or water droplets on the lens of the detector will absorb and reflect some of the light and may decrease the detector's ability to trigger an alarm during a fire situation. The effective detection distance of the sensors should therefore take this effect into account, and the lens surface of the detectors should be shielded to minimise this effect.

Development of frost and condensation on the detector lens could also desensitise the detectors and cause detection problems/delay. Water precipitation or sea spray may also freeze on the sensor surface in the form of ice and reduce the effectiveness of optical detectors. For this reason, some commercial optical detectors come with an option for a heated lens window, which prevents frost, condensation, and ice formation on the lens window. Such a solution is highly beneficial for maintaining detection performance under cold weather conditions.

If the detectors are exposed to sea spray, a layer of sea salt can deposit on the detector after the water has evaporated. This will reduce the image quality for video detectors and can lower the amount of radiation received by the lens for other optical sensors. Therefore, it is required to clean the sensors at certain intervals. Some commercial detectors come with an option which identifies reduced sensitivity due to a dirty sensor lens and can produce a warning signal for cleaning the sensor. This is considered highly beneficial for the timely maintenance of affected detectors.

6.4.7 Cargo characteristics

Fires inside steel containers are challenging to detect, because the smoke and heat are trapped inside for an extended period. Similarly, fires inside trailers may be detected with extended delays because many trailers have waterproof covers for their freight, and the cover can contain the smoke for a considerable amount of time. Fires inside vehicles can also go unnoticed for an extended period. For example, abnormal heat build-up in the traction battery of an electric car can be difficult to detect because the battery pack is inside a tightly sealed compartment placed under the vehicle (see LASH FIRE report IR09.15 [34] and annex B of deliverable D09.2 [1]). Another example is the smoke and heat from smouldering fires developing inside the passenger compartment of a car which can be trapped for many minutes before leaking out.

6.4.8 Nuisance alarms

During cargo loading and offloading, there will be a lot of activity and moving people and vehicles on the deck. Vehicles may have hot surfaces and the exhaust may look like smoke or hotspots from a fire.

As compared to the relatively static situation on the deck when the ship is at sea, this is a challenging scenario for the detectors, which may result in nuisance alarms without any fire.

At sea, the conditions are more static, but variations caused by shadows, changing sunlight, wind, and exhaust from the ship could also lead to challenges in terms of nuisance alarms.

It could be reasonable to establish two different alarm criteria: (1) for when the ship is either at sea with very limited activity on the ro-ro decks, and (2) for when the ship is at port with cargo loading and offloading operations. With such implementation of alarm criteria with adaptations for the different conditions during these two scenarios, the number of nuisance alarms may be reduced, thereby increasing the crew’s ability to respond quickly in case of an alarm that is caused by a real fire.

6.4.9 Other challenges

Apart from the factors discussed in the previous sections relating to the challenges of fire detection on ro-ro ships, there are other general factors that may challenge the detectors less frequently to different extents, such as radiated electromagnetic fields, vibrations, and cyclic damp heat. A non-exhaustive list of standard test methods for the evaluation of detectors against such factors can be found in Table 1 of EN 54-10 [26].

7 Evaluation criteria

Main author of the chapter: Davood Zeinali, FRN

Weather decks do not have standard detection systems at present, but any detection technology to be used on weather decks must: (1) provide effective detection performance better than or equal to that possible based on manual observations, (2) be compatible with the operational conditions on board, and (3) be cost-effective. Accordingly, the detection performance criteria are assessed firstly through experiments in a corresponding laboratory environment and then on board an operational ship, while separate assessments are made for the compatibility and cost-effectiveness criteria in collaboration with work package 5 of LASH FIRE which deals with ship integration (see deliverables D05.6 [35], D05.7 [36], D05.8 [37], and D05.9 [38]).

7.1 Performance

Detection systems have various applications and standards (e.g., see [26] and [39]), and thus the focus of the present project is not to assess the working mechanism of the systems or their compliance with standards. Rather, the goal is to assess the suitability of the underlying technology for the detection of fires in weather deck environments given the challenges discussed in section 6.4. Among other elements, the following main factors are assessed:

- **Wind:** the dispersion of smoke and the tilting of the fire plume due to wind and/or ventilation can make in-situ fire detection difficult. This is assessed via experiments to quantify how alternative detection systems are affected by such phenomena.
- **Light:** both artificial and natural sources of light can hinder fire detection and are considered in the evaluation of alternative detection systems via experiments.
- **Other environmental factors:** weather conditions (rain, snow, frost, condensation, sunlight, vibrations, wind, etc.) can affect the performance of the detection systems. This is assessed through operational evaluations on board a ship for over a year.
- **Cargo:** the normal operations related to cargo loading/offloading as well as the emission of (direct/reflected) light from the cargo surfaces can pose a detection challenge and lead to nuisance alarms. The obstruction of field of view could also be a problem. These factors are assessed through operational evaluations on board a ship for over a year.

7.2 Operational aspects and cost assessment

LASH FIRE deliverable D05.6 [35] discusses the ship integration requirements for the fire detection systems on weather decks, while deliverables D05.7 [40] and D05.8 [37] discuss the corresponding integration evaluations and cost assessment of the promising detection technologies based on the input provided by the lead author of the present document. Therefore, the information is not repeated here in detail. Instead, two examples are presented in this document to demonstrate the main concepts and to discuss the related insights.

7.2.1 Flame wavelength detectors for a generic ship

The system of flame wavelength detectors comprises of a few detector units as shown in Figure 2, and a cable connecting each detector back to the ship’s fire control panel for receiving and processing the alarm signals provided by the detectors. The mounting of the detectors is also done using a bracket attached to the ship, while a junction box may be used for better interface and maintenance. Each flame wavelength detector may also be accompanied by an optical camera (at an extra cost) to store footage of the area where fire is detected (e.g., 1-minute pre-event and 3 minutes post-event).

Figure 2: Example flame wavelength detector unit installed on board Hollandia Seaways for testing. The orange cable connects the detector to the fire control panel where the alarm signal is received and processed.

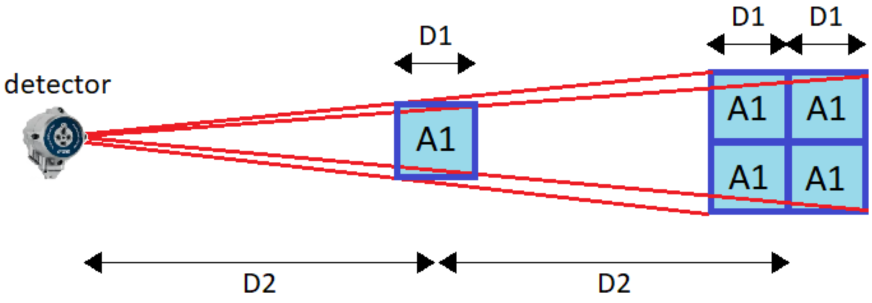


Figure 3: Square law between distance and area of detection (applicable when D2 >> D1): if an object that has an area of A1 is detectable at the distance of D1, detection at a distance of 2 x D1 requires nearly an area of 4 x A1.

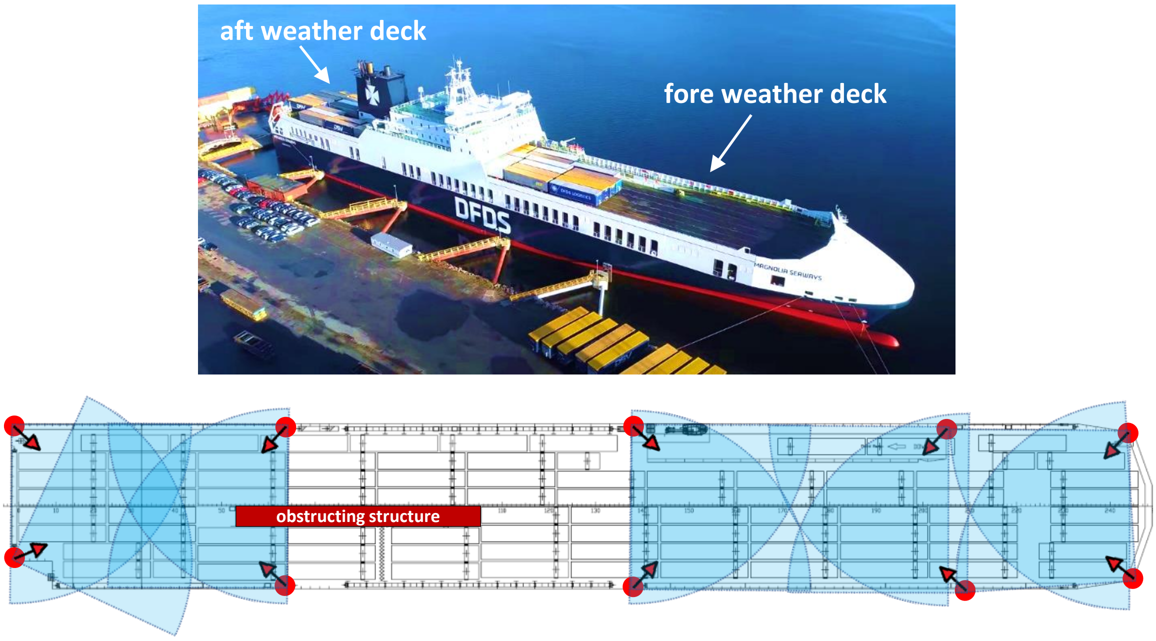


Figure 4: Integrated example of a flame wavelength detection system for the weather decks of Magnolia Seaways (ro-ro cargo ship shown above), with 6 flame wavelength detectors in the aft deck and 4 flame wavelength detectors in the fore deck.

The detection range for optical devices such as flame wavelength detectors follows the square law between distance and area of detection as long as the distance is high compared to the characteristic length of the object to be detected, such that detection at twice the distance requires nearly four times the area (or fire size), as illustrated in Figure 3. Accordingly, if a flame wavelength detector can detect a 40-kW fire at 30 m, detection at 60 m is expected to require a 160-kW fire.

The detection range of flame wavelength detectors also depends on their sensitivity settings, where low sensitivity settings may be used for close-range detection, while high sensitivity settings may be used for long-range detection. Correspondingly, the sensitivity settings may be fixed according to the application, desired detection time, and acceptable frequency of nuisance alarms. For instance, a 0.3 m x 0.3 m heptane pool fire may be detected at 15 m in nearly 1 s with low sensitivity settings, whereas the same fire may be detected from 60 m in nearly 3 s with high sensitivity settings, albeit more nuisance alarms may be triggered with the latter settings.

Most flame wavelength detectors provide a single output signal indicating the presence/absence of flames within the field of view, i.e., no X/Y coordinates are provided. However, array-type flame wavelength detectors have their field of view divided into several sectors, enabling them to detect in which part of their field of view the fire is located. Even with such type of detectors, however, often several detectors are needed in the detection system to ensure adequate coverage of the desired area based on the working range and acceptable sensitivity of the flame wavelength detectors.

Figure 4 illustrates an example flame wavelength detection system integrated for the weather decks of Magnolia Seaways (ro-ro cargo ship). The flame detectors in this example have low sensitivity settings with effective detection range of nearly 35 m at 90° horizontal angle and 75° vertical angle. A total of 700 m of power and signal cables is estimated for the proposed design. The cost estimate for this system is presented in Table 5. Examples for other generic ship types can be found in deliverable D05.8 [37].

Table 5. Estimated costs for the proposed flame wavelength detection system shown in Figure 4 for Magnolia Seaways.

Investment item	**Cost in EUR**
Purchase of system	60 590
Integration design and validation	8 000
Assembly/installation	38 440
Commissioning	1 000
Administration	12 000
Operator training	500
Total maintenance cost (assuming lifetime for existing ship is 22.9 years)	80 835
Total	**201 365**

7.2.2 Thermal imaging fire detection for a generic ship

The detection system based on thermal imaging is made up of a few infrared cameras (example shown in Figure 5), as well as some cables connecting the cameras back to the ship’s fire control panel and computer with the software required to receive and process the alarm signals and thermal images provided by the infrared cameras.

Infrared cameras are sensitive to hot surfaces, so they can detect areas that are hotter than other surfaces nearby. This can be used to detect potential ignition sources before any flame or smoke is released, but this may cause false alarms if the hot surface is not a real fire hazard. As a result, pre-registering areas with known hot objects at specific temperatures in the detection system can be an option for eliminating nuisance alarms generated by those sources of heat. Correspondingly, the proper commissioning of the thermal imaging fire detection system must consider the hot areas that are expected in normal operations. Moreover, the effectiveness of the thermal imaging cameras may be affected when their lens is covered by dirt, saltwater, or ice, so they require some general maintenance. The cameras also require free line of sight to the fire zone to trigger an alarm.

Figure 5: Example thermal imaging (infrared) camera installed on board Hollandia Seaways for LASH FIRE evaluations.

The detection range of infrared cameras may be as long as 250 m for objects as big as a human, but the detection depends also on the sensitivity settings of the camera, where low sensitivity settings may be used for close-range detection, while high sensitivity settings may be used for long-range detection. As infrared cameras are optical devices, their detection range also follows the square law between distance and area of detection illustrated in Figure 3, such that detection at twice the distance requires nearly four times the area (or fire size). In this regard, cameras installed on weather decks have the advantage of a wide view over the area. The location of the cameras and their sensitivity settings may be fixed according to the application, desired detection time, and acceptable frequency of nuisance alarms. Often several cameras are used to ensure adequate coverage of the desired area based on the working range and acceptable sensitivity of the cameras. In addition to triggering fire alarms, thermal imaging detection systems can provide the location of fire in terms of X and Y coordinates to autonomous fire suppression systems (refer to LASH FIRE deliverable D09.3 [2]).

Figures 6 and 7 show a thermal imaging detection system for the weather decks of Magnolia Seaways consisting of 2 infrared cameras for the aft weather deck and 2 infrared cameras for the fore weather deck. In this example, the cameras in this example have medium sensitivity settings allowing effective detection range of nearly 100 m at 25° horizontal angle and 20° vertical angle. A total of 350 m of power and signal cables is estimated for the proposed design. Table 6 shows the cost estimate for this system. Examples for other generic ships can be found in deliverable D05.8 [37].

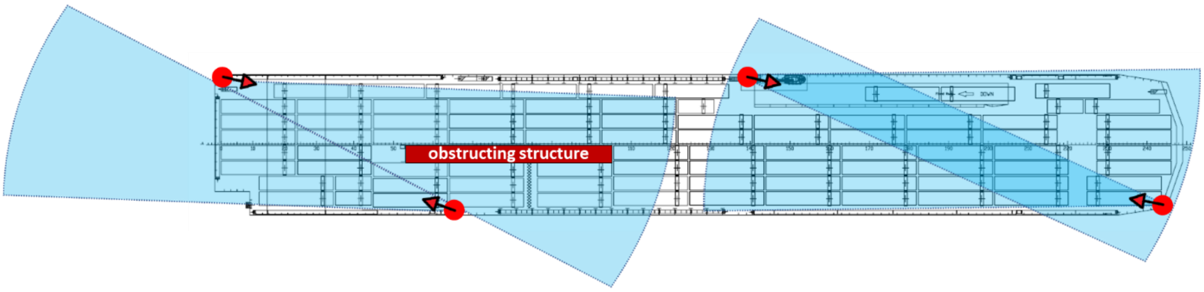


Figure 6: Integrated example of a thermal imaging fire detection system for the closed ro-ro spaces on Magnolia Seaways consisting of 4 cameras for the main deck (top figure) and 2 cameras for the tank top (bottom figure).

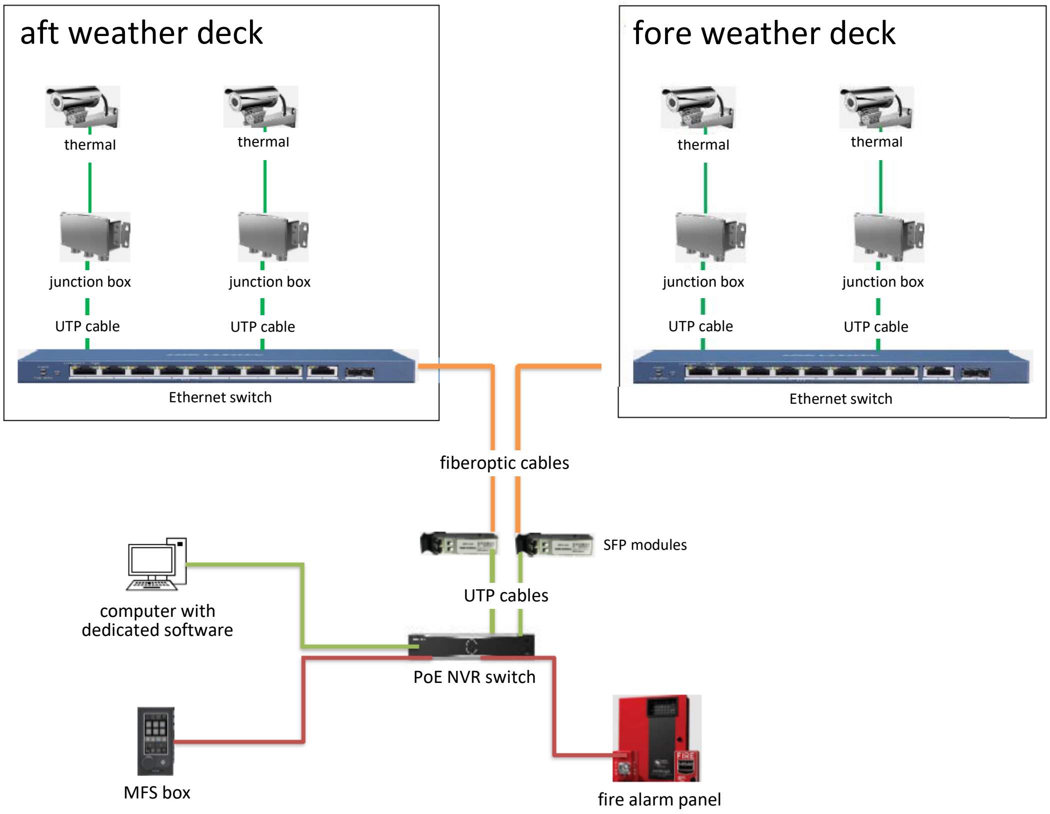


Figure 7: Concept of a detection system based on thermal imaging (infrared) cameras for the weather decks of Magnolia Seaways, i.e., on the aft and fore weather decks as shown in Figure 6.

Table 6. Estimated costs for the proposed thermal imaging detection system shown in Figure 7 for Magnolia Seaways.

Investment item	**Cost in EUR**
Purchase of system	49 100
Integration design and validation	8 000
Assembly/installation	20 900
Commissioning	1 000
Administration	12 000
Operator training	500
Total maintenance cost (assuming lifetime for existing ship is 22.9 years)	80 835
Total	**172 335**

7.3 Conclusions

The cost of thermal cameras themselves is approximately 3-4 times that of flame wavelength detectors. However, an overall cost assessment made for ro-ro cargo ships as part of LASH FIRE deliverable D05.8 [37] shows that the total lifecycle cost is about 15% higher in the case of flame wavelength detectors application, exclusively due to higher installation costs (more pieces of equipment and cabling needed, leading to higher installation costs). Regarding ro-pax ships, the comparison of two systems is again in favour of IR thermal cameras, although the relative difference is only a few percent. Nevertheless, the cost of the systems is only one factor determining their attractiveness. System performance on board the ship is arguably a more important factor that can affect the attractiveness of the systems.

8 Laboratory experiments

Main authors of the chapter: Ellen Synnøve Skilbred, Reidar Stølen, and Davood Zeinali (FRN)

8.1 Objective

The LASH FIRE laboratory experiments allowed evaluating the detection capabilities of a wide range of detectors for fire scenarios applicable both to weather decks and to open ro-ro decks, discussed comprehensively through deliverables D09.2 [1] and D09.3 [2]. However, based on the initial review of the technologies discussed in chapter 6, flame wavelength detectors and thermal imaging detection systems are the focus of the laboratory experiments discussed in the present document, with the objective to discuss their suitability for weather decks under different fire scenarios. This is while the final operational evaluations on board a ro-ro ship included additional types of detectors such as video fire detectors which were also tested through laboratory experiments as discussed in deliverable D09.2 [1] and D09.3 [2].

Note that different detectors have different evaluation standards or no standard at all depending on their underlying technology, such that the performance of different detectors is not easily comparable. Moreover, each detection technology is sensitive to certain signature parameters from the fire, so each detector type is expected to detect certain types of fires. Consequently, rather than universally endorsing one technology over another, the following chapter provides indicative results with the aim to help identify the weaknesses and strengths of different systems to demonstrate their merit for weather deck applications.

8.2 Experiments with ISO 8-ft containers

8.2.1 Experimental set-up

As listed in Table 7, six detectors were evaluated through two series of experiments. The first series of experiments included three flame wavelength detectors and two IR thermal cameras, while the second series of experiments included two flame wavelength detectors and three IR thermal cameras. All the detectors were initially checked to confirm that they provide an alarm signal when a fire was placed within their field of view. Moreover, all the devices had default sensitivity settings for detection. One of the flame wavelength detectors had a built-in camera that could show live images from the area where the fire was detected. Another one was an array type flame wavelength detector that could pinpoint the location of the flame within the sectors of its field of view. The thermal imaging cameras had different software features to monitor and record the temperature trends at different locations over time.

Table 7: Detectors evaluated for weather deck applications through two laboratory test series (1 and 2).

Detector ID	**Detector type**	**Test series**
FD1	IR array flame wavelength detector (16x16 IR3 sensors)	1 and 2
FD2	Triple-IR flame wavelength detector (with a built-in camera)	1 and 2
FD3	Triple-IR flame wavelength detector	1
IR1	IR thermal imaging camera 1	1 and 2
IR2 a/b*	IR thermal imaging camera 2	1 and 2
IR3**	IR thermal imaging camera 3	2
* IR2a used settings that allowed vehicle nuisance source discrimination. IR2b used default settings without this feature. ** IR3 here means the third IR camera, and it is not to be confused with triple-IR technology used by FD1, FD2, and FD3.		

The two series of experiments were conducted inside the large test hall of RISE Fire Research in Trondheim, Norway, with a total floor area of 16 m x 36 m and a ceiling height fixed at 16 m as shown in Figure 8. The test area was made with 4 8-ft ISO shipping containers made of steel and measuring 2.43 m x 2.2 m x 2.26 m (Length x Width x Height) which were spaced 0.5 m apart, placed 0.2 m above the floor on supporting blocks at their corners as shown in Figure 9.

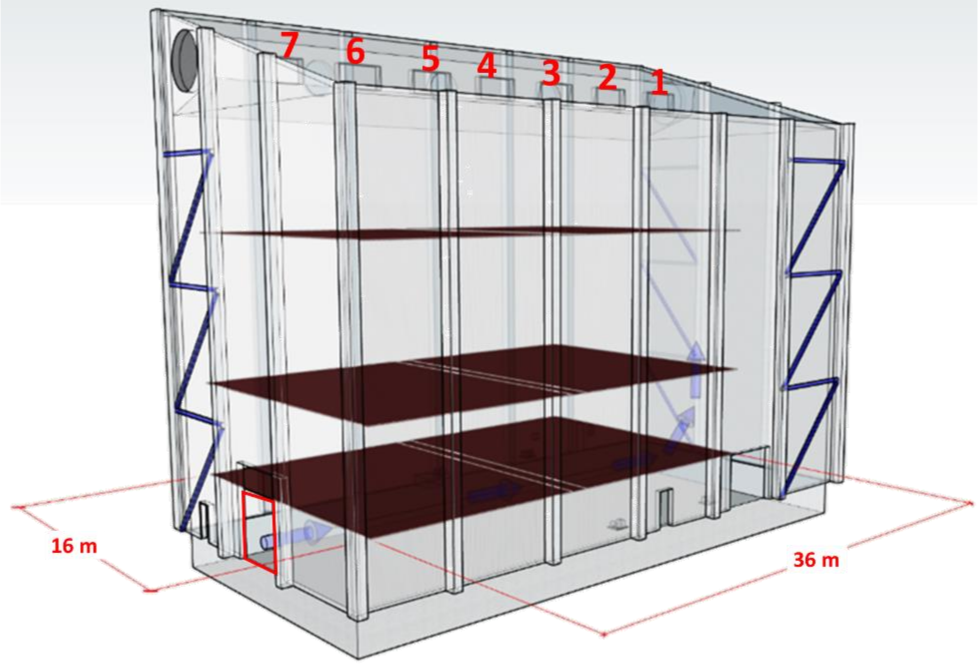


Figure 8: The large fire test hall at RISE Fire Research in Trondheim, Norway. The purple arrows indicate the wind direction across the test hall with the use of ventilation fans at the top of the hall (numbered 1 to 7 with red digits) and an open western gate measuring 4.5 m wide and 4.3 m high (marked with a red rectangle). The adjustable ceiling measures 25 m long and 16 m wide which was fixed at the height of 16 m during the weather deck tests.

Figure 9. Setup used during the first series of experiments. The yellow rectangle shows the detectors mounted on the wall.

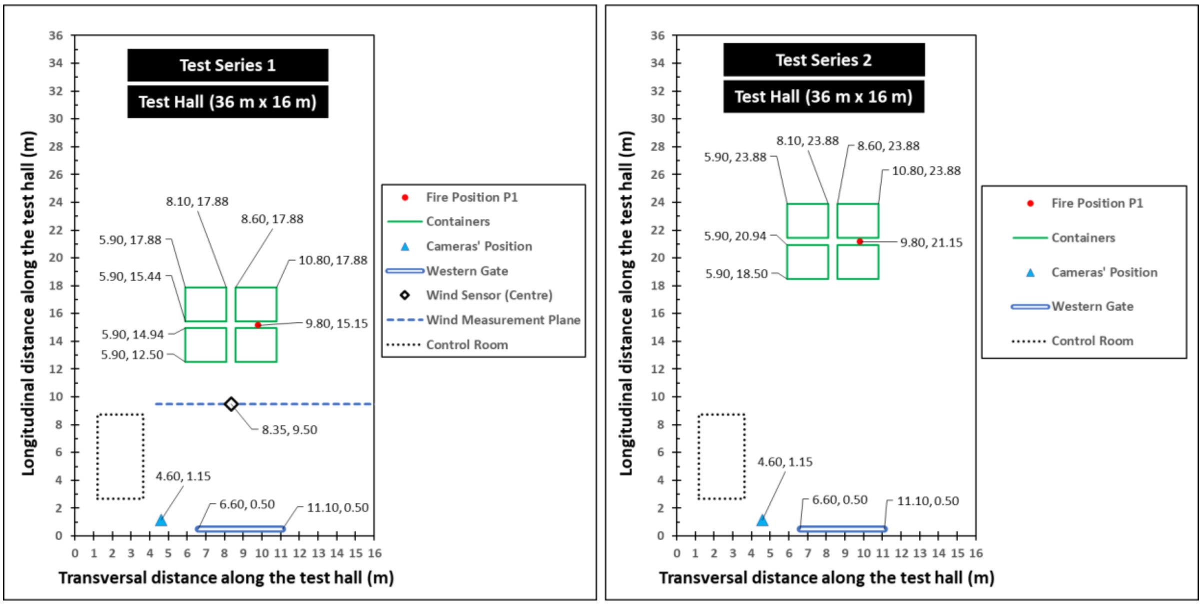
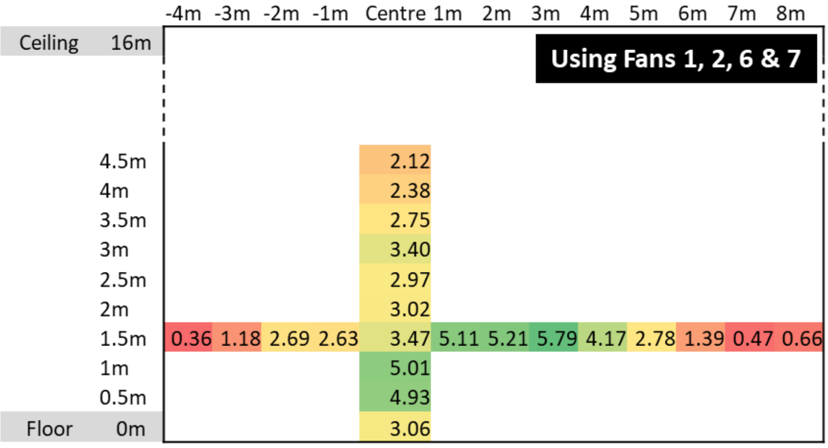


Figure 10: Top view of setup used in the two series of weather deck tests. The numbers indicate the X and Y positions of items in the test hall. The four green squares indicate the outlines of the 8-ft ISO containers. The detectors were mounted at the height of 5.5 m during the first test series and at 4 m during the second test series, while the ceiling height was 16 m in both test series. The experiments with wind were conducted only during the first test series. Wind measurements were made across the transversal plane marked with a dotted line (data shown in Figure 11).



	-4m	-3m	-2m	-1m	Centre	1m	2m	3m	4m	5m	6m	7m	8m
Ceiling 16m													
4.5m					2.12								
4m					2.38								
3.5m					2.75								
3m					3.40								
2.5m					2.97								
2m					3.02								
1.5m	0.36	1.18	2.69	2.63	3.47	5.11	5.21	5.79	4.17	2.78	1.39	0.47	0.66
1m					5.01								
0.5m					4.93								
Floor 0m					3.06								

Figure 11: Wind velocities (m/s) along the wind measurement plane shown in Figure 10 with active fans 1, 2, 6 & 7. The fan locations are shown in Figure 8.

In the experiments without wind, no use was made of the hall's ventilation fans (shown in Figure 8), and the gates of the test hall were closed, such that the only air circulation in the hall was that created by the fire. In the experiments with wind (conducted only during the first series of experiments), wind conditions were generated by extracting air using the ventilation fans and by opening the test hall's western gate (measuring 4.5 m wide and 4.3 m high as shown in Figure 8), creating wind blowing from west to east across the test hall. The wind velocities were characterised along the transversal wind measurement plane shown in Figure 10, the results of which are presented in Figure 11.

The fire positions are shown through Figures 12 and 13. As the fire position in different tests was different relative to the containers, the fire was not directly visible to the detectors in some scenarios. More specifically, positions P5 and P6 were the only positions openly visible to the detectors (see Figure 12).

Figure 12: The test containers from the viewpoint of the detectors on the wall. Fire positions P5 and P6 were directly visible to the detectors, while the other fire positions were shielded between or inside the containers (see Figure 13).

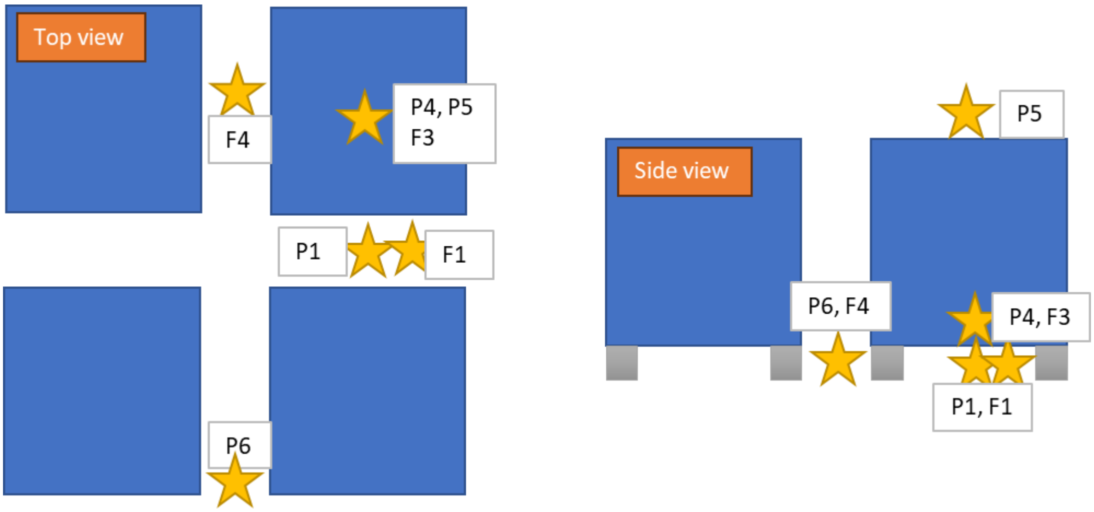


Figure 13: Evaluated fire positions relative to the steel containers. The fire positions in test series 1 are marked with P1, P4, P5, and P6, while the positions in test series 2 are marked with F1, F3, and F4. Note that positions P4 and F3 are identical, but the door of the container was open for P4 and closed for F3.

The height of the detectors' position was 5.5 m in the first test series and 4 m during the second test series, while the horizontal distance to the detectors' position from the centre of the container setup was 14 m during the first test series and 20 m during the second test series (coordinates shown in Figure 10).

Several experiments during the second test series were specifically aimed at investigating the detection of flame reflections. In these experiments, the fire was not directly visible in the field of view of the detectors. Instead, the corrugated steel wall of a container was used to reflect the light from the fire toward the detectors. During these tests, the distance of the container with respect to the fire and the detectors was varied from 14.5 m to 5 m as shown in Figure 14.

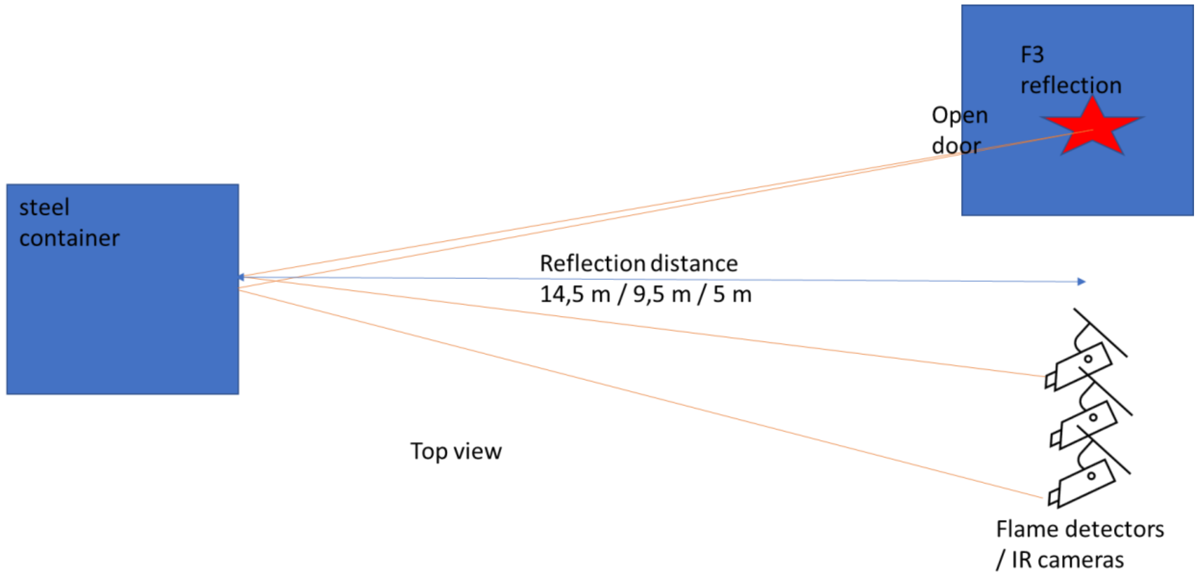


Figure 14: Top view sketch of the test configuration used in the reflection tests in the second test series. The fire was placed in a container with open doors outside the field of view of the detectors and a steel container was used as a reflective surface with different distances from the fire and detectors.

Three types of fire sources were used during the weather deck laboratory experiments: beechwood sticks on a hot plate, and two liquid pool fires.

The beechwood sticks on a hot plate followed the setup described in EN 54-29 annex I for a smouldering wood fire [41]. The beechwood sticks were sized 20 mm x 25 mm x 75 mm and heated on the hot plate to release a light grey smoke without ignition, as shown in Figure 15. The hot plate had a 220-mm diameter grooved surface and an approximate power rating of 2 kW, capable of reaching 350°C in 4 minutes.

The liquid pool fires were created with methylated spirits (ethanol) and n-Heptane according to the guidelines of EN 54-10 [26]. The fuel was added to a water base in pool trays of different dimensions. In the first test series, a square tray measuring 30 x 30 cm^2, a circular tray with a diameter of 10 cm, and a circular tray measuring 15 cm in diameter were used. In the second test series, heptane was the only fuel source used, with rectangular pools of three sizes, namely 30 x 30 cm, 50 x 50 cm, and 60 x 60 cm. The corresponding average heat release rate of each fire was estimated at 65, 302 and 364 kW, respectively (calculated based on the fuel amount, burn time, as well as assumptions of a heat of combustion of 33 MJ/litre, a constant mass loss rate over the burn time, and complete combustion). The maximum flame height is shown in Figure 16. The flames from the smallest pool fire used in test series 2 did not reach the top of the containers, while the flames of the medium sized pool extended beyond the top intermittently, and the largest pool fire extended beyond the top of the containers for most of the time. Hence, only the two larger fires were visible from the location of the wall-mounted optical detectors. Both the heptane fires and ethanol fires produced visible smoke and luminous flames, but the smoke was more visible for the heptane fires and its flame was more luminous.

In addition to the stationary fire scenarios, two experiments were conducted with moving heat sources. One experiment involved a diesel-powered forklift driven inside the test area to see if the hot exhaust could trigger nuisance alarms, and the second experiment involved a Ø 10 cm liquid pool fire with ethanol which was moved slowly towards the detectors to examine the sensitivity of the detectors' different alarm settings according to the distance of the fire from the detectors.

Figure 15: Beechwood sticks on a hot plate generating light grey smoke without flames (as described in EN 54-29 [41]).

Figure 16: Maximum extension of the flame lengths for the three heptane pan fires of 30 x 30 cm (left), 50 x 50 cm (middle) and 60 x 60 cm (right).

8.2.2 Results and discussion

The results of the weather deck experiments are presented in Tables 8 and 9 for test series 1 and 2, respectively, in terms of the time from ignition to detection for the different experiments sorted based on the fire position.

The beechwood sticks smouldering on a hot plate were detected by the thermal imaging cameras, but there were no open flames during the test, so the flame wavelength detectors did not trigger an alarm. With the use of thermal imaging, the tests with the hot plate without wood sticks resulted in a shorter detection time than when wood sticks were used on the plate. This suggests that the visible portion of the hot plate surface was more influential for detection using thermal imaging than the smouldering wood sticks (compare tests 50, 52, and 53 in Table 8).

The flame wavelength detectors often had detection times below 30 s for the cases where flames were directly visible to the detectors, i.e., in ignition positions P5 and P6, as well as ignition position F4 when the flame from the pool fire extended beyond the height of the containers, except for some cases of 10-cm-diameter pool fires which were too small at location P5. In test 66 with a wind velocity of 5 m/s, the 10-cm diameter heptane fire was also detected, perhaps because the wind helped the fire grow slightly bigger.

Table 8: Detection time of detectors (in seconds) during weather deck experiments in the first test series, sorted based on the ignition position, with detectors' height of 5.5 m and different wind conditions (0 or 5 m/s wind speed at the height of 1 m at the central wind sensor position shown in Figure 10). 'ND' indicates 'No Detection'.

						Flame wavelength detectors			**Thermal imaging cameras**		
Test nr	**Fuel**	**Fuel amount**	**Pool size**	**Ignition position**	**Wind (m/s)**	**FD1**	**FD2**	**FD3**	**IR1**	**IR2a**	**IR2b**
56	Ethanol	1 liter	30 x 30 cm	P1	0	ND	ND	ND	ND	ND	ND
45	Heptane	1 liter	30 x 30 cm	P1	0	ND	ND	ND	156	ND	ND
64	Heptane	1 liter	30 x 30 cm	P1	5	ND	ND	ND	ND	ND	ND
60	Ethanol	1 liter	30 x 30 cm	P4	0	ND	ND	ND	ND	ND	ND
43	Heptane	1 liter	30 x 30 cm	P4	0	ND	ND	ND	114	ND	ND
63	Heptane	1 liter	30 x 30 cm	P4	5	ND	ND	ND	ND	ND	ND
48	Ethanol	0.01 liter	Ø 10 cm	P5	0	ND	2	ND	19	ND	22
67	Ethanol	0.01 liter	Ø 10 cm	P5	5	ND	14	ND	19	ND	24
49	Heptane	0.01 liter	Ø 10 cm	P5	0	ND	4	ND	23	ND	60
66	Heptane	0.1 liter	Ø 10 cm	P5	5	69	46	134	57	ND	83
50	Hot plate, no sticks	0 Sticks	Hot plate	P6	0	ND	ND	ND	51	165	78
52	Hot plate, no sticks	0 Sticks	Hot plate	P6	0	ND	ND	ND	57	160	93
53	Hot plate + wood sticks	6 Sticks	Hot plate	P6	0	ND	ND	ND	85	337	171
55	Ethanol	1 liter	30 x 30 cm	P6	0	4	0	8	2	6	5
57	Ethanol	0.01 liter	Ø 10 cm	P6	0	45	6	ND	23	59	25
58	Ethanol	0.01 liter	Ø 10 cm	P6	0	108	15	ND	ND	ND	ND
68	Ethanol	1 liter	30 x 30 cm	P6	5	7	4	9	5	26	16
70	Ethanol	0.01 liter	Ø 10 cm	P6	0	ND	77	249	178	ND	ND
44	Heptane	1 liter	30 x 30 cm	P6	0	5	0	8	9	4	8
59	Heptane	0.1 liter	Ø 10 cm	P6	0	72	57	135	105	ND	ND
61	Heptane	0.1 liter	Ø 10 cm	P6	0	39	4	298	12	42	14
65	Heptane	1 liter	30 x 30 cm	P6	5	5	0	6	0	5	8

Table 9: Detection time of detectors (in seconds) during weather deck experiments in the second test series with heptane pool fires series, sorted based on the ignition position, with detectors' height of 4 m and no wind. 'ND' indicates 'No Detection', i.e., the detector did not detect the fire. 'Yes' indicates detection happened while the timing was not recordable. Empty fields indicate that the detector was not active during the test. IR1 to IR3 are simply infrared thermal cameras 1 to 3, and there is no difference in their technology.

							Flame wavelength detectors		**Thermal imaging cameras**		
Test no	**Pool size**	**Fuel amount (l)**	**Ignition position**	**Reflection distance (m)**	**Burn time (s)**	**Average HRR (kW)**	**FD1**	**FD2**	**IR1**	**IR2b**	**IR3**
3	30 x 30 cm	1	F1		533	62	ND	ND			ND
4	30 x 30 cm	1	F1		469	70	ND	ND		ND	ND
9	30 x 30 cm	1	F1		530	62	ND	ND	ND	ND	ND
16	30 x 30 cm	1	F1		522	63	ND	ND	ND	ND	ND
20	30 x 30 cm	1	F1		478	69	ND	ND	81	ND	ND
2	50 x 50 cm	1.5	F1		131	378	27	17			22
5	50 x 50 cm	3	F1		304	326	33	19		ND	21
6	50 x 50 cm	3	F1		310	319	35	13		yes	13
10	50 x 50 cm	3	F1		378	262	20	17	yes	ND	11
17	50 x 50 cm	3	F1		371	267	28	11	yes	yes	22
18	50 x 50 cm	3	F1		378	262	25	20	ND	yes	19
7	60 x 60 cm	4	F1		367	360	17	12		yes	11
19	60 x 60 cm	4	F1		359	368	20	14	12	yes	16
11	30 x 30 cm	0.5	F3		402	41	ND	ND	yes	ND	193
12	50 x 50 cm	1.5	F3		not registered		ND	ND	yes	ND	yes
13	30 x 30 cm	1.5	F3		722	69	ND	ND	yes	ND	172
21	30 x 30 cm	0.2	F3	14.5	103	64	ND	ND	ND	ND	ND
22	30 x 30 cm	0.2	F3	14.5	100	66	ND	21	ND	ND	ND
23	50 x 50 cm	0.5	F3	14.5	83	199	ND	1	29	ND	ND
24	60 x 60 cm	0.7	F3	14.5	83	278	ND	3	17	ND	ND
25	60 x 60 cm	0.7	F3	9.5	77	300	10	2	5	27	ND
26	60 x 60 cm	0.7	F3	5	83	278	4	2	9	25	ND
14	30 x 30 cm	1	F4		465	71	ND	58	ND	ND	ND
15	50 x 50 cm	3	F4		371	267	26	2	157	ND	9

The fire positions P1 and P4 were not visible from the viewpoint of detectors, and thus no alarms were triggered for those fire positions, except during tests 43 and 45 where the heated surface or hot gases were detected by IR thermal camera 1. For other ignition locations not directly visible to the detectors, no fire was detected by the flame wavelength detectors, except in tests with 50x50 and 60x60 cm^2 heptane fires which extended beyond the height of the containers as well as in the reflection tests 22 to 26 where a reflection path was made specifically toward the detectors (see Figure 14). Most of the 30 × 30 cm^2 heptane pool fires were not detected as the flames from these fires did not reach the top of the containers (see Figure 16). Thermal imaging camera IR1 detected more of these fires than the other detectors. Thermal camera IR3 (here IR3 means third camera, not triple-IR technology) was the most sensitive to the heptane pool fires as it detected almost all the 50 × 50 cm^2 and 60 × 60 cm^2 fires. IR1 and IR2 detected some similar fires and some different fires. A slight difference appears for heptane pool fires in position F3 and F4, where IR1 detects most of the fires while IR2 does not. These differences are expected to be due to the differences in the detection threshold sensitivity settings of the cameras.

The test with a diesel-powered forklift driven into the test hall caused an alarm to be triggered by two of the three IR thermal cameras due to hot surfaces on the exhaust pipe, but none of the flame wavelength detectors responded to this. The software of thermal camera IR2 was set up with two independent alarm settings, namely, one which was the default settings (IR2b shown in Table 8) and another which included a vehicle discrimination algorithm (IR2a shown in Table 8). The algorithm disregarded moving hot surfaces of vehicles below a certain temperature if the hot surfaces started cooling after the vehicle had stopped. This feature prevented the forklift from triggering an alarm, while an alarm was triggered in the mode where this feature was disabled. The default mode in general detected the fires faster than the mode with the vehicle discrimination. Moreover, in the tests with fires in position P5 on top of the container, only the mode without the vehicle discrimination feature triggered an alarm. Thermal camera IR1 triggered alarms faster than IR2 in most tests, including the forklift nuisance alarm test, as it was set to activate the alarm at a lower temperature. This illustrates that selecting and setting the alarm threshold will be a trade-off between the detection time and the nuisance alarm frequency.

For the heptane and ethanol pool fire tests 58 and 59, the base of the fire was shielded from the detectors, and only the flame was visible, otherwise these fires were similar to those of tests 57 and 61. In test 58, none of the IR thermal cameras were able to detect the ethanol fire, and in test 59, only one of the IR thermal cameras was able to detect the heptane fire. This suggests that an important part of the detection mechanism for the thermal camera was the hot surfaces at the base of the fire. This is while the flame wavelength detectors were much less influenced by the shielding of the fire base in their results, confirming that the visible flame tip is enough for these detectors to detect the fire.

Among the tested flame wavelength detectors, FD2 was usually the first detector to trigger an alarm, followed by FD1 and finally FD3. This indicates that the FD2 sensor was more sensitive or configured with a more sensitive setting than the FD1 detector. Moreover, this corresponds well to the sensitivity tests that were conducted by moving a small 10-cm diameter ethanol fire slowly towards the detectors and marking the maximum distance where each of the detectors triggered the alarm. These measurements of maximum detection distance are presented in Table 10 along with those of thermal imaging cameras IR1 and IR2. The differences in the detection distance are assumed to be mainly caused by software and alarm threshold settings, which can be adjusted for each detector to optimise the balance between early detection and the frequency of nuisance alarms. Nevertheless, it must be noted that the detection of a 10-cm diameter fire from over 30 m by thermal camera IR1 and the detection from 23 m by FD2 are testament to the long-range detection capability of thermal cameras and multi-spectral IR flame wavelength detectors.

Table 10: Maximum distance where the different detectors triggered the alarm based on a Ø10 cm ethanol fire. IR1 and IR2 are thermal imaging cameras, and FD1 to FD3 are flame wavelength detectors.

Detector ID	**Maximum distance of detection for a Ø10 cm ethanol fire**
IR1	31 m
FD2	23 m
IR2b	14 m
FD1	13 m
FD3	11 m

A unique advantage of the IR thermal cameras was their ability to detect a completely concealed fire inside a closed container, as in tests 11, 12, and 13 (Table 9), where the hot container roof was detected. Figure 17 shows an example image from the moment of detection by thermal camera IR1 during test 13. Thermal camera IR3 recorded maximum temperatures between 130°C and 190 °C on top of the containers during this test.

Figure 17: A fire inside a closed container detected by a thermal imaging detection system during test 13 (Table 9). This image is captured by thermal camera IR1, showing the hot roof of the container with a red colour. This fire was not detected by the flame wavelength detectors as no flames were visible outside the container.

The thermal imaging cameras were also able to detect 50 x 50 and 60 x 60 cm^2 pool fires between two containers, due to the heat reaching the top of the containers. An example of this is shown through the thermal image in Figure 18 from thermal camera IR3 in test 19 (Table 9) where the heat from the fire is clearly visible. The tip of the flame was occasionally visible on top of the containers. The graph of the temperatures from the area of flickering flame tip can be seen in Figure 19 based on measurements by thermal imaging cameras IR2 and IR3. In this graph, the fluctuating temperature is clearly visible from 0 to 300 seconds corresponding to the burn time of the fire. The recorded temperatures from IR2 and IR3 cameras correspond well with each other up to the point where IR3 peaks at 200°C while IR2 continues to show the measured temperature values. Two additional points are also recorded by IR2, one on the roof of a hot container next to the fire and one on the roof of a cold container that is not near the fire, although these temperatures were lower than the temperatures from the flame plume and have not been high enough to trigger the alarm based on the detection threshold settings.

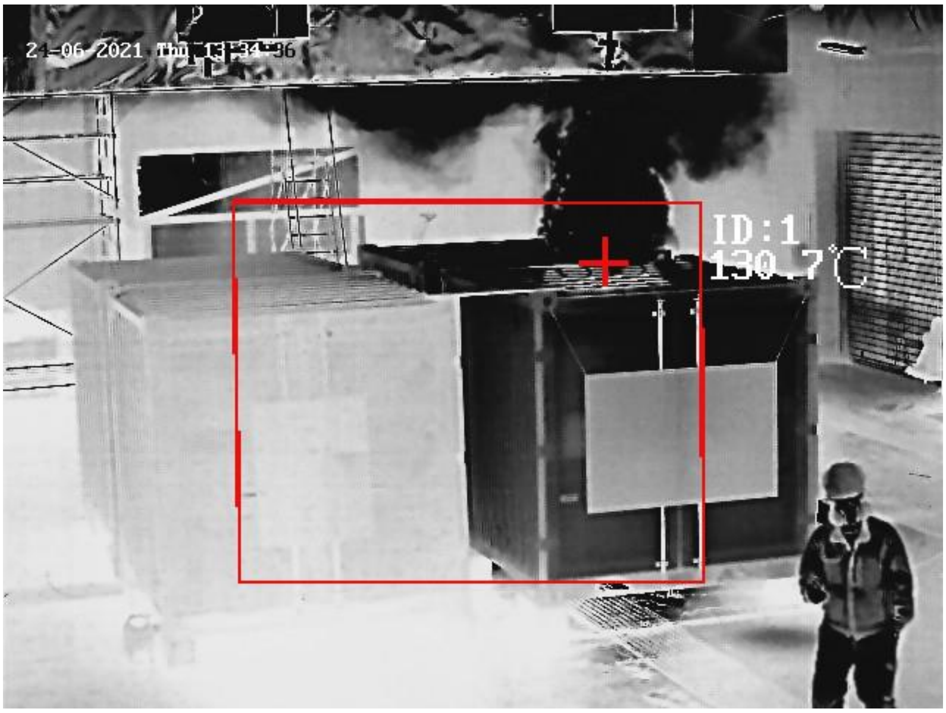


Figure 18: Infrared image from IR3 camera during test 19. An alarm is triggered, and the recorded maximum temperatures are presented in Figure 19. High temperatures are illustrated with dark tones as seen on the two rightmost containers, the smoke plume from the fire source between them, and the person visible in the bottom right corner.

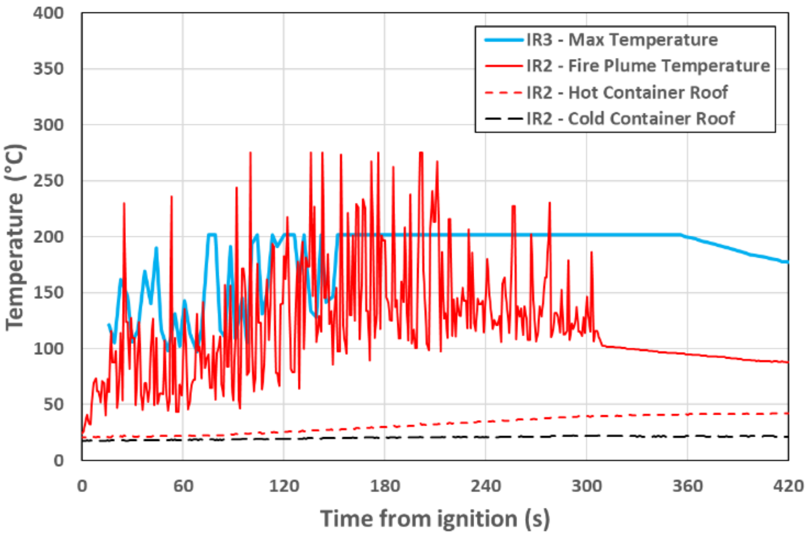


Figure 19: Flame and container roof temperatures measured using thermal imaging cameras IR1 and IR2 during test 19 (described in Table 9). The first 300 s correspond to the burn time of the heptane pool fire.

The reflection tests with 50 x 50 and 50 x 60 heptane pool fires at the distance of 9.5 and 5 m resulted in a successful detection by both the flame wavelength detectors and the thermal cameras. For the distance of 14.5 m, however, identifying the flame reflection proved to be more difficult and thus fewer detections were made. Moreover, as suggested by the measurements of the thermal camera IR2 shown in Figure 20, the properties of the reflecting surface determined the magnitude of the perceived temperatures. As Figure 20 indicates, the corrugated steel container located just 5 m away from the flame is perceived to have a maximum temperature of 42.8°C, while the aluminium scaffolding located 25 m from the flame is perceived to have a temperature of 128.6°C. This illustrates that the reflectivity of the surface is more influential in determining its perceived temperature than the distance of the surface to the fire. Moreover, this indicates that the painted steel container walls are not very efficient in reflecting the relevant wavelengths of thermal radiation detected by the infrared cameras. It is expected that this affects flame reflection detection using flame wavelength detectors and thermal imaging cameras in the same way.

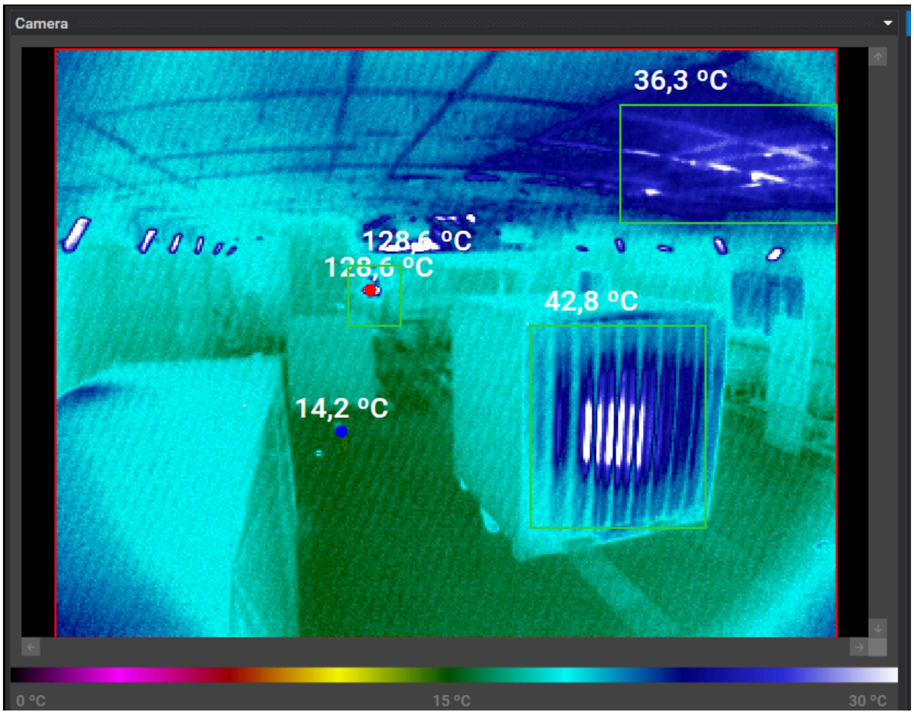


Figure 20: Image captured by a thermal camera during a flame reflection experiment (test 26 in Table 9). The corrugated steel wall of the container reflecting the flame at 5 m from the fire shows a maximum temperature of 42.8 °C. This is while the aluminium scaffolding 25 m away from the fire shows 128.6 °C. The heated ceiling shows 36.3 °C, and the concrete floor shows 14.2 °C.

8.3 Propane burner calibrations for wind tests and onboard evaluations

According to EN 54-10 [26], a heptane pool fire can be used for the testing of optical detectors such as flame wavelength detectors. However, an equivalent gas burner had to be produced during the LASH FIRE project because the standard testing method using a heptane pool fire was not practical for tests on the DFDS ship for onboard evaluations. The designed gas burner measures 30 × 30 × 30 cm^3 operated using a small propane bottle (see Figure 21). The inside of the gas burner was filled with lightweight clay aggregates that disperse the propane uniformly, creating a flame that looks very much like that of the heptane pool fire described in EN 54-10 [26]. The gas burner was calibrated such that its heat release rate (~120 kW), flame height (~0.9-1.1 m), and heat fluxes (~5 kW/m^2) were comparable to those of the standard heptane pool fire (see data shown in Figure 22). The heptane burner used for the calibrations was almost identical in construction, except the inside of it contained water at the bottom and heptane at the top during the test. This was to make sure that the heptane pool surface had the same free height from the top edge of the tray as mentioned in EN 54-10 [26], i.e., 45 mm after adding 500 ml heptane with 3% toluene.

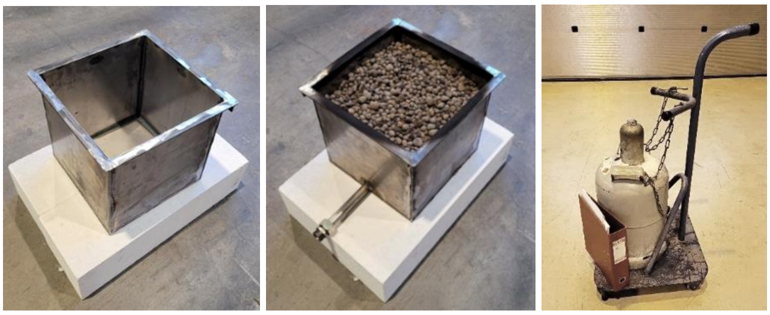


Figure 21: Tray for the heptane pool fire (left) and the equivalent gas burner (middle) used with a propane bottle (right).

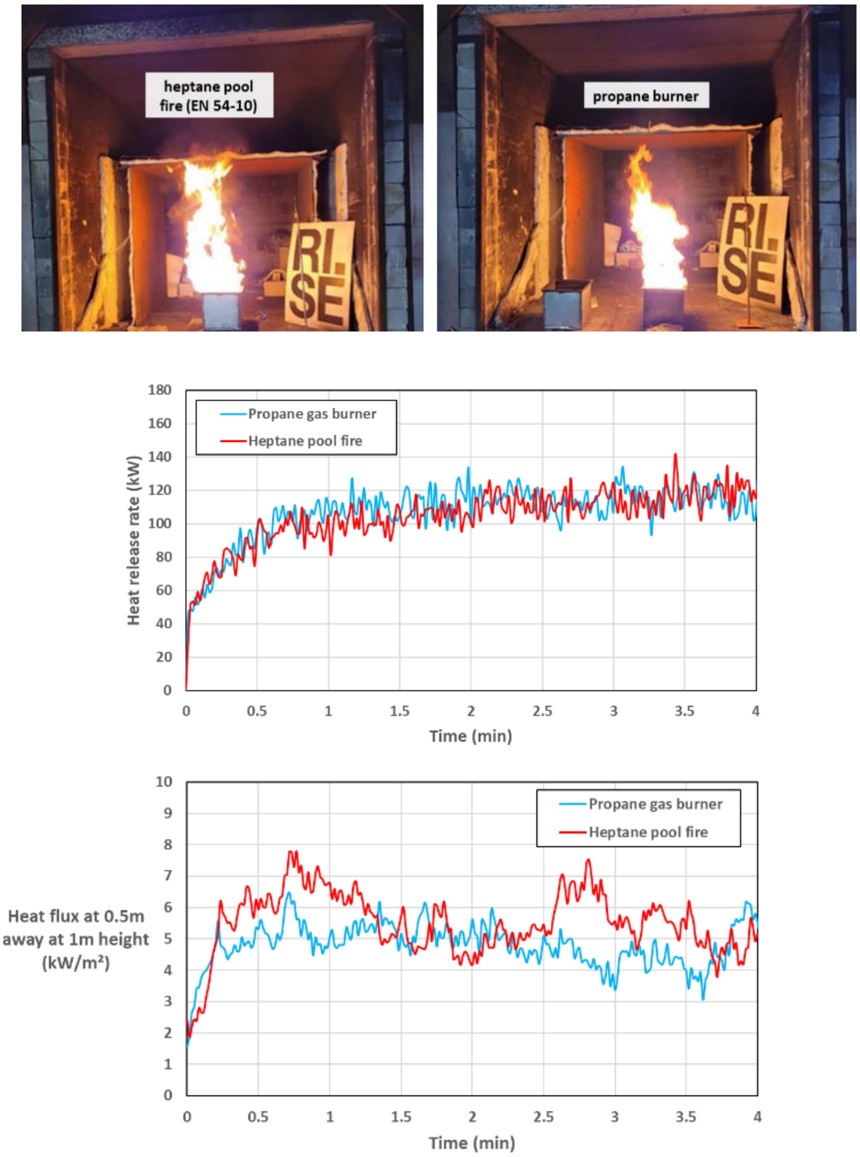


Figure 22: Snapshots of standard heptane fire versus the propane fire (top), heat release rate of each fire (middle), and heat fluxes (bottom) measured at 0.5 m horizontal distance from the edge of each burner at the height of 1 m.

Figure 23 shows the heat release rate of the burner when operated at the maximum possible power using the propane bottle shown in Figure 21. Using the maximum power of the burner (140-kW peak), the maximum flame height was slightly higher than 1.5 m which is enough to be visible above the height of most passenger cars. Therefore, optical detectors such as video fire detection systems and flame wavelength detectors are expected to detect this flame within seconds if the camera/detector sees the fire area or the flame reflections. However, the flame height is not high enough to be visible above the height of trucks. Therefore, optical detectors are not expected to see this fire behind trucks unless the fire gets bigger or reflected toward the detector.

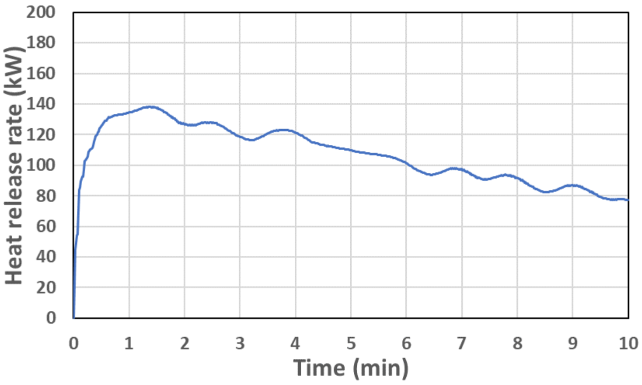


Figure 23: Heat release rate of the burner operated at the maximum possible power using the bottle shown in Figure 21.

8.4 Wind experiments

High wind speeds can affect fire dynamics and thereby the ability of detection systems to detect the fire. Several tests were conducted to investigate this effect, complementing the lower wind speed tests discussed in the previous section (Table 8). These tests are expected to be highly relevant for detectors on the weather deck which can have windy conditions.

8.4.1 Experimental set-up

The wind experiments were conducted using the propane gas burner discussed in the previous section and the heat release rate shown in Figure 23. Fans were placed at 3.45 m distance from the burner, and a wind speed sensor was placed in between at 1.5 m from the burner and 1.95 m from the fans at the height of 0.5 m as shown in Figure 24. A CCTV camera and a thermal camera were used to monitor the flame. These were installed on a tripod placed on a scaffolding at 10 m height with a horizontal distance of 27.1 m from the burner. Nine experiments were conducted in total with wind speeds ranging from 4.5 to 11 m/s.

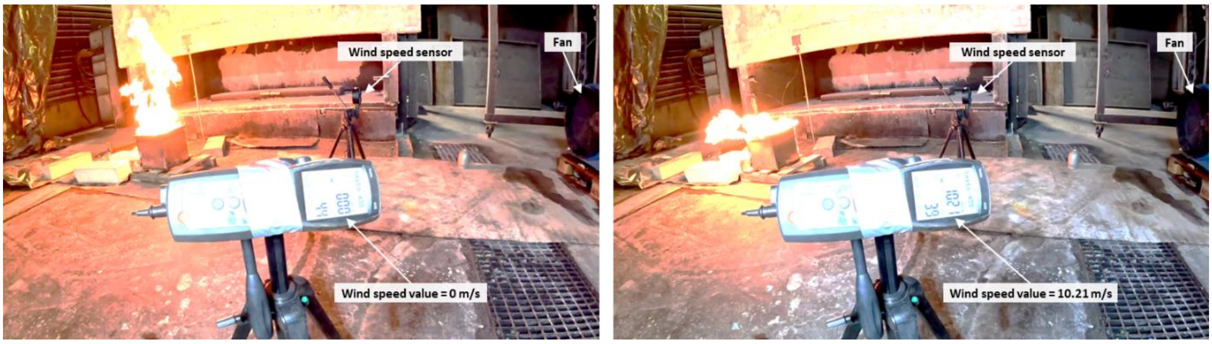


Figure 24: Snapshots showing a wind test with the propane burner before and after fan activation.

8.4.2 Results

In the case of images captured by regular video cameras, the fire appeared much larger sometimes due to the reflections of the flame on nearby surfaces (see snapshots in Figure 25). In the case of thermal images from the thermal camera, however, the wind made the flame occupy fewer pixels in general (see snapshots in Figure 26).

Figure 25: Wind effects visible in footage snapshots of a flame captured by a camera at 27.1 m horizontal distance and 10 m height: the wind causes the fire to appear smaller sometimes (middle photo) and bigger at some other times (right photo) due to the image saturation and flame reflections from nearby surfaces.

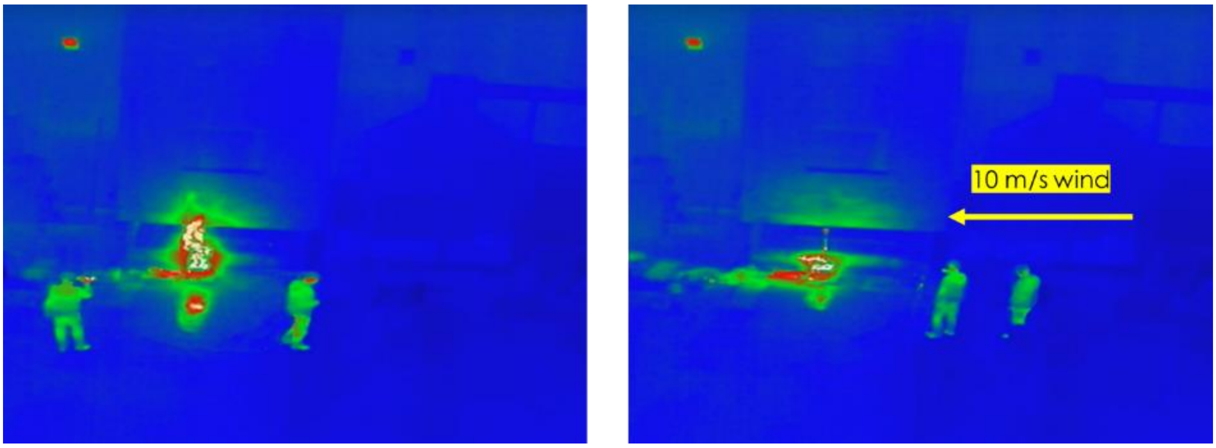


Figure 26: Wind effects visible in footage snapshots of a flame captured by a thermal imaging camera at 27.1 m horizontal distance and 10 m height: the wind causes the flame to occupy fewer pixels, which makes it more difficult to detect.

Table 11: Average number of image pixels occupied by the flame in thermal and regular video footage from the wind tests.

Wind source	**Regular video footage**		**Thermal imaging footage**		**% of change with wind for regular video camera**	**% of change with wind for thermal imaging camera**
	Flame pixels without wind	**Flame pixels with wind**	**Flame pixels without wind**	**Flame pixels with wind**		
Small fan (~4.5 m/s)	24054	6840	5921	1758	-72%	-70%
Big fan (~10 m/s)	27288	12797	4692	1518	-53%	-68%
Both fans (~11 m/s)	23322	18719	3066	1941	-20%	-37%

Table 11 shows the flame size in the footage of each camera type in terms of average number of image pixels occupied by the flame in 20 random footage frames. As the pixel numbers suggest, lower wind speeds in the order of 4.5 m/s cause the biggest amount of change in the recorded size of the flame, whereas the highest wind speeds in the order of 11 m/s cause the smallest amount of change in the recorded size of the flame. This is because the higher speeds cause the flame to pulsate back and forth more chaotically, such that the overall recorded size of the flame on average is still considerable compared to the original flame size recorded without wind. This is while lower wind speeds cause more regular flame tilting that keeps the size of the flame smaller than that with no wind. As a result, it is expected that lower wind speeds cause more challenge for fire detection and confirmation than high wind speeds, although a threshold of high wind speed can be expected beyond which the flame is not identifiable or simply blown out.

The results also suggest that the change in flame size due to wind is bigger in thermal images than in regular video images for all cases with wind, except the case with the small fan where both image types have the same level of change (see percentages in Table 11). The smaller change in more cases with regular video is because their images tend to get saturated by highly luminous sources such as flames, making them appear bigger and thus offsetting the reduced flame size due to wind. Reflections over shiny surfaces are also perceived more strongly in regular video images. In contrast, thermal images tend to be more precise in their localisation of the actual flame boundaries, with minimal image saturation. This precision quality of thermal images is usually beneficial for surveillance of hot areas, but it may make manual confirmation of fires more difficult in occasions with windy conditions, especially with lower wind speeds which reduce the flame size the most (note that overwhelming image saturation and high-speed changes due to strong wind can also confuse some video analytics algorithms). However, systematic fire detection based on temperature thresholds in the thermal image is still highly reliable. To the contrary, video detection systems that rely on flame flicker patterns across a certain number of pixels and in the vertical direction may have more difficulty detecting a tilted flame under windy conditions in a systematic way.

8.5 Fire experiments with automatically guided fire monitors

In the case of autonomous suppression systems which must activate and operate automatically, the detection system must provide the respective trigger signal based on the corresponding detected location of the fire. In this regard, a description of the remote-controlled and autonomous fire-extinguishing systems developed for weather decks during the LASH FIRE project is discussed through deliverable D10.3 [42], with onboard demonstration of the solutions discussed in deliverable D10.2 [43]. Regarding the developed alternative fixed fire-fighting systems and their large-scale validations, the reader is referred to deliverables D10.1 [44] and D10.4 [45], respectively.

Fire monitors are suppression systems suitable for weather decks which can direct a stream of water or foam at any desired direction. Autonomous fire monitors require the detection system’s input regarding fire location in terms of X and Y coordinates, i.e., the horizontal and vertical distances with respect to a reference point defined for the suppression system. However, the X and Y coordinates must be available from two different locations, because correctly aiming each fire monitor requires a three-dimensional analysis of the fire location in the space using the third coordinate Z regarding depth. The relevant detection systems considered suitable for this fire localisation purpose during the LASH FIRE project are primarily IR array flame detectors, but also video fire detection and thermal imaging detection systems.

The LASH FIRE experiments on the guidance of autonomous fire monitors are discussed in detail in deliverable D10.3 [42]. Figure 27 shows an illustration of the setup used for the experiments, which included fire detection testing, precision testing using one autonomous fire monitor, precision testing using two autonomous fire monitors, testing the influence of wind (generated using a snow cannon), and testing the influence of rain and fog (generated using a snow cannon and a fire hose). Each tested autonomous system was comprised of two IR array flame wavelength detectors, a fire monitor, as well as associated software and hardware enabling the system to detect and track the presence, three-dimensional size, and location of a fire in real time automatically and autonomously.

Upon the identification of a fire, the software dynamically guided the fire monitor to direct the water stream toward the fire location without any human intervention, although the autonomous function could be overridden by an operator at any time if desired. For a detailed description of the system specifications and the analysis of the test results, the reader is referred to chapter 8 of deliverable D10.3 [42].

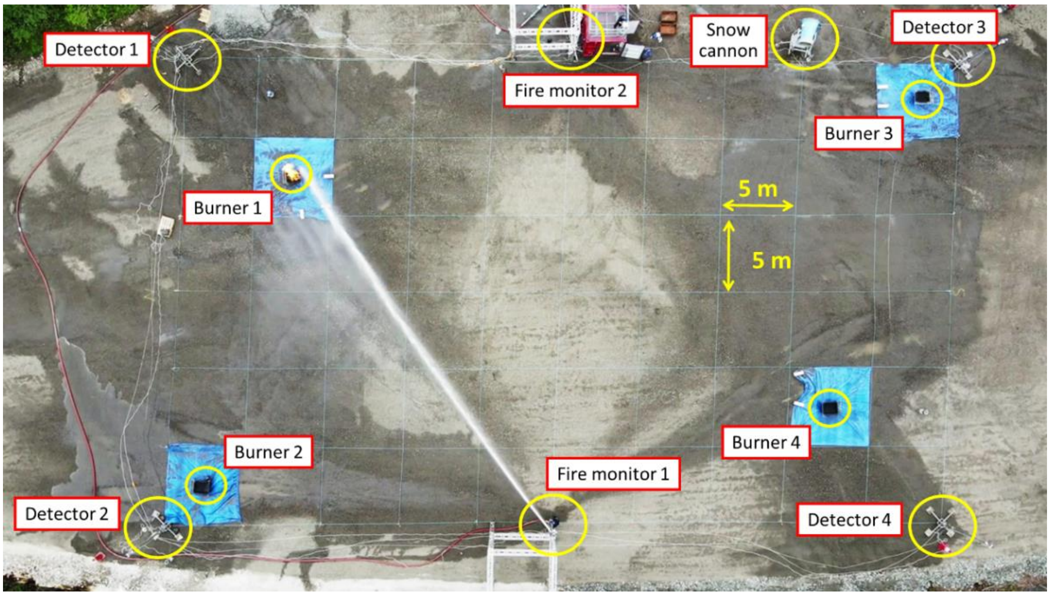


Figure 27: Setup of LASH FIRE experiments with autonomous fire monitors (suppression system for weather decks) [42]. The photo shows an experiment where one fire monitor is projecting water towards a fire identified using two IR array flame wavelength detectors. The test area is 50 m by 30 m and has been marked on the ground with squares measuring 5 m by 5 m.

8.6 Large-scale fire suppression experiments with fire monitors

Several large-scale fire extinguishment tests were performed outdoors at the test facility of RISE Fire Research in Trondheim, Norway, which are discussed in detail in deliverable D10.3 [42]. For these experiments, the fire monitors were programmed to direct the water stream with a predefined pattern around the fire area to quantify the optimal suppression effect possible using one or two fire monitors from different angles, while the autonomous functionality of the fire monitors with guidance using an optical detection system was already evaluated in a separate study as explained in the previous section. Nevertheless, two thermal imaging cameras and a flame wavelength detector were installed beside the fire monitors at the height of 7 m with the purpose to evaluate their potential use during large-scale fire suppression on weather decks, which is the focus of the present section.

8.6.1 Experimental set-up

The test area measured 40 m by 30 m, representing a section of a weather deck. The experiments simulated a freight truck trailer fire with cargo containers on both sides and consisted of a main array of stacked idle wood and plastic pallets, which was partly covered by a steel roof as shown in Figure 28. Parallel with and 0.5 m to the sides of the main array, 20-foot cargo containers were positioned to mimic the compactness of vehicles, trailers, and other cargo on a weather deck.

As shown in Figure 28, the fire source consisted of 224 pallets (192 wood and 32 plastic pallets), arranged in 16 stacks, i.e., 8 stacks along the length and 2 stacks along the width, with each stack containing 14 pallets along the height (12 wood pallets with 2 plastic pallets on top). Three, 2-inch remote controlled fire monitors were positioned at a height of 7.2 m above the ground, and tests were conducted with one monitor and two monitors from various angles. Moreover, tests with both short and long pre-burn times were conducted to evaluate early or late fire suppression initiation scenarios.

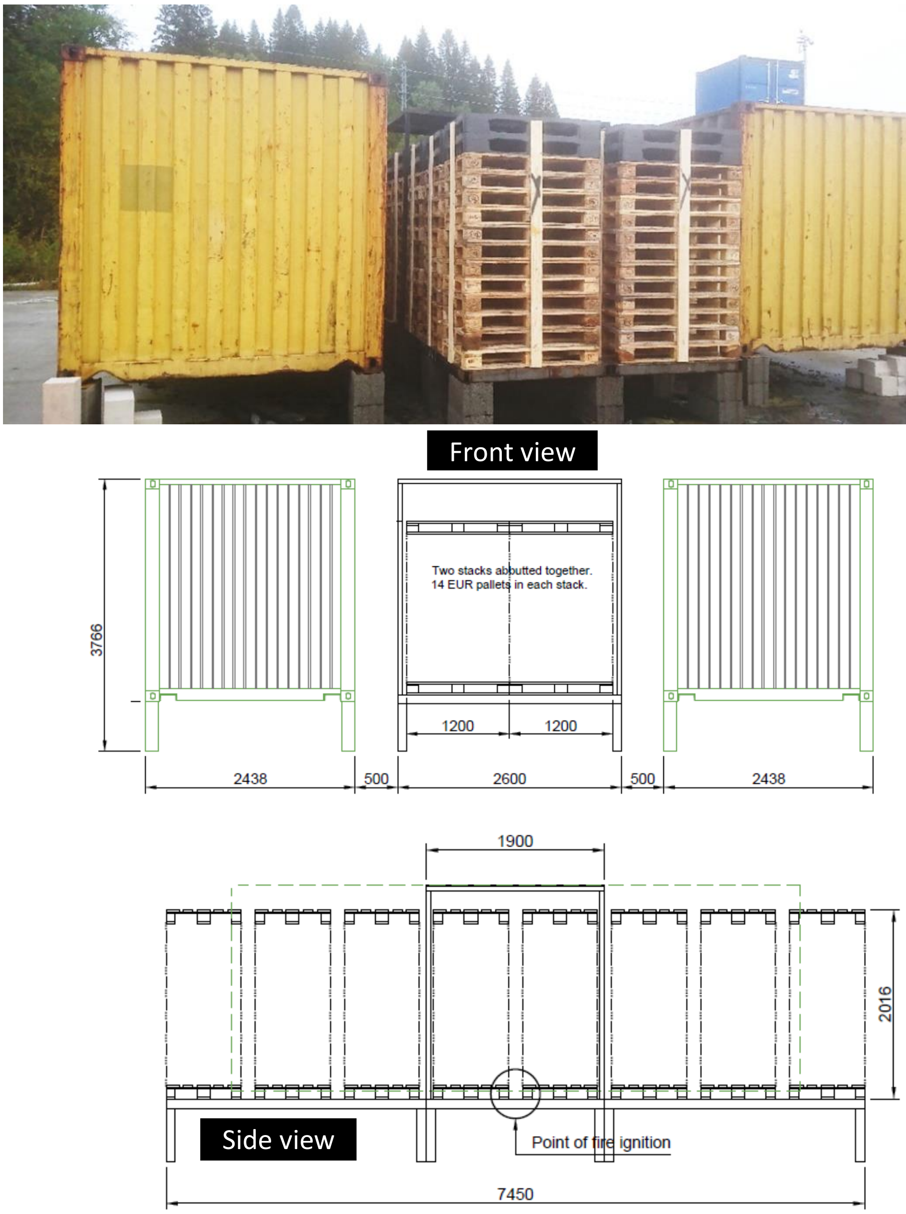


Figure 28: The arrangement of the containers and the pallets used as a fire source for the large-scale fire suppression experiments with fire monitors for a weather deck environment. Top: photo showing the front view of the setup. Middle: front-view sketch of the setup showing dimensions in mm. Bottom: sideview sketch of the mid-section of the setup containing the stacks of Euro pallets (12 wood and 2 plastic pallets on top in each stack), the ignition source (a heptane tray located at the centre of the setup as characterised in the text), and the roof structure in the middle of the setup, with dimensions in mm.

The roof structure above the fuel stacks was made of steel sheets and measured 2.6 m wide and 1.9 m long. The intent of the roof was to prevent suppression or extinguishment of the initial fire, especially when using a short delay time from fire ignition to the application of the suppression agent. The vertical and horizontal supports of the roof were cooled by water circulating through the square iron structure. The vertical distance measured from the ground to the top of the roof and the tops of the surrounding cargo containers was about 3,15 m. The length of the cargo containers was less (nominally 6,1 m) than the overall array.

Figure 29: Photo showing the moment of activation of two of the three fire monitors (marked as A, B, and C) during a late-suppression scenario (300-s waiting time).

The fire was initiated using a heptane tray sized 1200 mm (L) by 150 mm (W) by 150 mm (H) filled with a depth of 20 mm (3,6 l) of heptane on a 20-mm layer of water (3,6 l). The heptane fuel on the tray was ignited by a torch. The fire tray was on the platform used to stack the pallets and was placed symmetrically between the centremost flue space of the array of pallets as shown in Figure 28.

The fires were allowed to develop until flames were visually observed above the top of the array by a person in front of the setup. Thereafter, either a 30 s or 300 s delay time was applied before the application of water using fire monitors was initiated. The shorter delay time was designed to simulate rapid activation by an autonomous system, while the longer delay time simulated manual activation and remote-controlled operation by the ship's crew (a photo from this latter scenario is shown in Figure 29).

8.6.2 Results of flame wavelength detector and thermal imaging

The application of water on the fire generated major amounts of smoke and water vapor. As example snapshots in Figure 30 illustrate, the footage of the regular camera did not allow seeing the areas behind the smoke, while the footage of the thermal camera still highlighted the hot regions behind the smoke very effectively. For this reason, regular video cameras are expected to be less useful during the suppression of large-scale fires. In contrast, the thermal cameras are expected to be very useful for continued monitoring of fire development and suppression owing to their ability to see through thin smoke. Thermal cameras can also help identify people in the area better than regular video cameras as highlighted in Figure 30. On the downside, as indicated in Figure 30, the reflections of the fire on the wet ground or other shiny surfaces are perceived as significant heat sources by thermal cameras and flame wavelength detectors. Such reflections of flame radiation can be easily misinterpreted as secondary sources of fire (as demonstrated through reflection tests described in Table 9) which can distract the resources of the fire extinguishment system if guided by detectors relying on flame radiation for detection.

The water stream from the fire monitors occasionally blocked the field of view of thermal imaging and regular video cameras (see examples in Figure 31). This blockage of the field of view is due to the water's ability to attenuate thermal radiation [33], and it highlights how the surveillance coverage may be compromised by the water stream either partially or completely if camera placement is not appropriate. Moreover, this highlights the importance of having several thermal cameras at different positions to be able to view the fire area from different angles with less compromise in the surveillance.

Figure 30: A snapshot from a regular video camera (top) and a snapshot from a thermal imaging camera (bottom) during a fire suppression experiment with two fire monitors in the late fire suppression scenario (300-s waiting time). The persons in the background and the flame reflections on the wet ground have been highlighted manually.

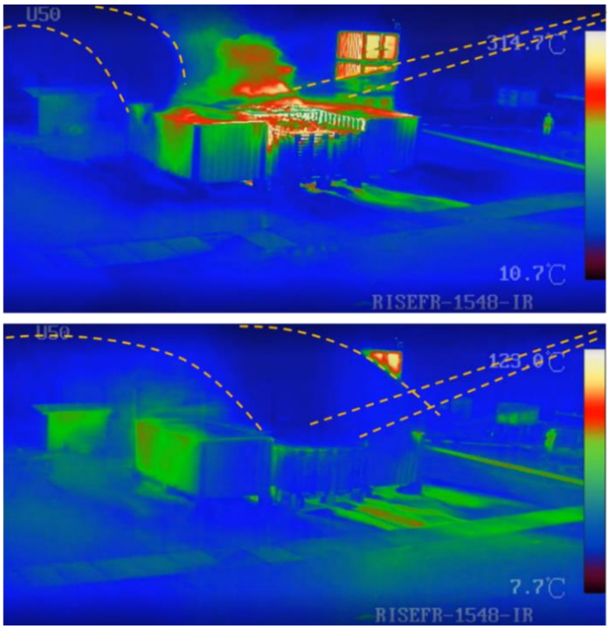


Figure 31. Blockage of view in thermal images due to two water streams (dashed lines) from fire monitors placed at the top right and top left corners of the view. For this view angle of the thermal camera, the fire monitor at the top right corner causes minimal blockage, whereas the fire monitor at the top left corner causes much more blockage of the fire area when its water stream is at the centre of the view (in the bottom figure).

Table 12: Fire alarms registered by the tripe-IR flame wavelength detector located beside fire monitor B shown in Figure 32.

Test #	Fire monitors used*	Scenario**	Alarm #	Alarm time after flames become visible in the video footage, and the subsequent status of fire
1	A and C with water	Early suppression	1	**34 s** Water was applied and the flame was extinguished soon after.
2	C with water	Early suppression	1	**40 s** Water was applied, but a small flame which was shielded continued to burn for ~25 min.
3	A and C with foam	Early suppression	1	**40 s** Foam was applied and the flame was extinguished soon after.
			2	**3 min, 21 s** Small flames reappeared and quickly extinguished again by the foam.
4	C with foam	Late suppression	1	**53 s** Fire grew without intervention.
			2	**12 min, 26 s** Foam was applied from over 9 minutes earlier, but the fire was still big. At this moment, slight changes by the foam in the view triggered a new alarm. Fire continued to grow.
			3	**15 min, 32 s** Foam caused small changes in the view that triggered a new alarm. Major fire continued to burn.
5	C with water	Late suppression	1	**45 s** Fire grows without intervention.
			2	**5 min, 33 s** Water was applied and the big fire was extinguished, but a small flame which was shielded continued to burn.
			3	**20 min, 41 s** Some flames reappeared and quickly extinguished by the water.
6	A and C with water	Late suppression	1	**43 s** Fire grew without intervention.
			2	**5 min, 53 s** Water was applied and the fire was extinguished soon after.
7	B and C with water	Late suppression	1	**48 s** Fire grows without intervention.
			2	**5 min, 44 s** Water was applied and the fire was extinguished soon after.
8	A and B with water	Late suppression	1	**49 s** Fire grows without intervention.
			2	**5 min, 48 s** Water was applied and the fire was extinguished soon after.
* The locations of fire monitor A, B, and C are shown in Figure 29. ** ‘Early suppression’ started ~30 s after flame observation, while ‘late suppression’ started ~300 s after flame observation.				

According to the fire alarm data in Table 12, the triple-IR flame wavelength detector succeeded in detecting the initial flames very quickly, but the continuous presence of flames in the field of view caused the detector to become saturated, such that it stopped reporting the flames until fire suppression started and interfered with the flames (see photos from the detector’s built-in video camera in Figure 32). This relates to a well-known flame detection problem which often arises due to the presence of strong non-flame sources of thermal radiation in the background of a flame, making the flame difficult to detect via its radiation signature [46]. Due to this effect, triple-IR flame wavelength detectors are known to be saturated by strong sources of thermal radiation in their field of view. In the LASH FIRE experiments, the continuous presence of the flame itself saturated the triple-IR detector and made the flame difficult to detect in a continuous way, but an IR array detector may have performed better. For the guidance of autonomous fire extinguishment monitors as described in section 8.5, a lack of continuous information supply from the detector is expected to prevent quick adjustments of the water aiming system according to the instantaneous developments of the fire area. Therefore, the best course of action for the autonomous fire monitor is to primarily rely on the first fire detection information for guiding the water nozzle, while later the nozzle must continue to focus on the initial spot until new fire location information becomes available from the detector.

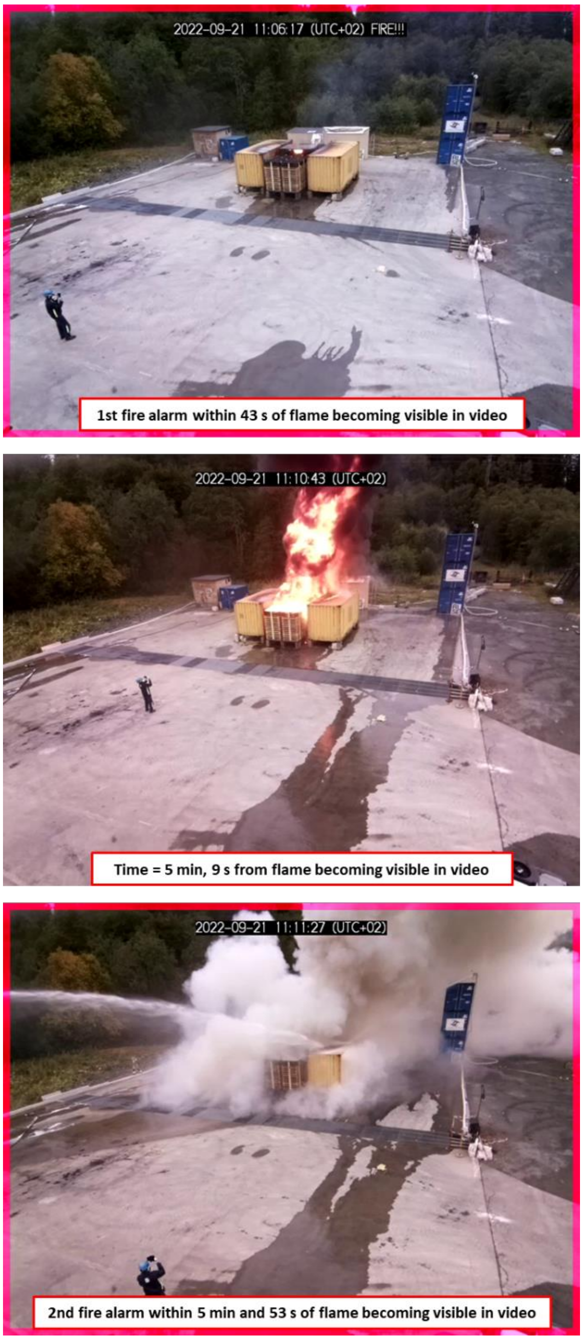


Figure 32. Video images from the built-in camera of the triple-IR flame wavelength detector during test 6 described in Table 12 (late suppression with fire monitors A and C shown in Figure 29). Top figure shows the first fire alarm. Middle figure shows moments before the activation of fire monitors. Bottom figure shows the second fire alarm after the activation of fire monitors.

8.7 Main findings from laboratory tests

The fire experiments with ISO 8-ft containers suggest that both flame wavelength detectors and thermal imaging detection systems can provide early detection at long distances when they receive the required signal from the fire. More specifically, open flames were rapidly detected by flame wavelength detectors when the flame was in their effective range, while thermal imaging cameras could detect all hot regions and identify warm objects like people. This helped with the detection of completely concealed fires by thermal imaging, but it also made thermal cameras more susceptible to nuisance alarms from hotspots that did not represent a fire hazard. For instance, the hot exhaust pipe of a diesel forklift caused a nuisance alarm by the thermal imaging cameras, whereas flame wavelength detectors did not trigger a nuisance alarm for this source. One thermal camera had an option to detect the nuisance alarm sources on moving vehicles, but the detection with this feature was slower. Therefore, it is expected that either the detection temperature threshold must be increased to avoid nuisance alarms from the vehicle exhaust pipes, or a vehicle discrimination algorithm must be used. However, the result would be a trade-off between detection speed and frequency of nuisance alarms.

Thermal imaging cameras were able to detect an openly visible hot plate with beechwood sticks smouldering on top. Flame wavelength detectors could not detect this heat source because no flames were visible in this fire scenario. Ethanol and heptane pool fires were detected mostly when their flames were visible to the detectors, but thermal cameras occasionally detected the fires indirectly via heated surfaces or hot gases. Most remarkably, in the experiments where the fire was concealed inside a container, the heated roof was detected by thermal imaging, while flame wavelength detectors did not trigger an alarm because no flames were visible to the detectors.

Applying a wind speed of up to 5 m/s did not significantly affect the detection performance of thermal cameras and flame wavelength detectors during the experiments with ISO 8-ft containers, such that no clear trend of effects from wind could be seen in their detection time results.

Applying wind speeds from ~5 to 11 m/s against a propane burner fire, it was found that the flame size in the footage of thermal and regular video cameras changed more dramatically for lower wind speeds than for high wind speeds. Moreover, the change in flame size was more dramatic for thermal imaging cameras than for regular video cameras. As a result, manual observations of the flame in the footage are expected to be more challenging in windy conditions. As for systematic fire detection, it is expected that thermal imaging systems based on temperature thresholds can detect the fire more reliably than video fire detection systems, although it is noteworthy that thermal imaging systems can be prone to frequent nuisance alarms if the detection criteria of maximum temperatures or rate of rise of temperatures are not fixed with the right sensitivity thresholds.

During the large-scale fire extinguishment tests, it was found that thermal imaging cameras could see through thin smoke, making them useful for continued monitoring of fire development during fire suppression when a large amount of smoke was produced. However, the reflections of the fire on the wet floor were perceived as significant heat sources by thermal cameras and flame wavelength detectors. Such flame reflections can be easily misinterpreted as secondary sources of fire that distract the resources of the fire extinguishment system if guided by detectors relying on flame radiation for detection. Moreover, the flame wavelength detector was saturated by the continuous presence of big flames in its field of view, preventing it from providing continuous updates on the presence of the flame. Therefore, it is expected that for larger fires, the initial fire detection information can be used to aim the water nozzle of an autonomous fire monitor system at the fire, while later the nozzle must continue to focus on the initial spot until new fire location information becomes available from the detector.

Different detection zones and alarm criteria need to be tested on board for thermal imaging systems utilising local temperatures, maximum area temperatures, and the rate of rise of temperatures, to prevent frequent nuisance alarms. This means that there should be a period of system commissioning and optimisation to adapt the alarm criteria for each given environment and installation. For flame wavelength detectors, it is expected that nuisance alarms will not be an issue, but the planning of detector positioning must be made using models of coverage area based on the available mounting positions, the required coverage, the effective detection distance of the detectors, and the sensitivity settings for each detector.

9 Onboard evaluations

Main author of the chapter: Davood Zeinali (FRN)

Based on the conducted laboratory evaluations, several candidate detectors were selected and tested on board Hollandia Seaways (DFDS ro-ro cargo ship) between February 2022 and July 2023. The present chapter discusses the operational evaluations as well as the fire experiments performed on board in the beginning and after one year for the valuation of the residual sensitivity of the detectors.

9.1 Objective and selection of detectors

The main objective of the evaluations on board Hollandia Seaways was to provide a realistic validation for the operational performance of the detection systems. Another important objective was to evaluate how the alarm threshold settings can be optimised for the different systems to balance early detection with a low number of nuisance alarms during normal operations.

For weather deck evaluations, a hybrid detector (video fire detector + thermopile heat detector), two thermal imaging detectors, three flame wavelength detectors (two IR3 and one IR array), and a video flame detector were installed on the weather deck of Hollandia Seaways to investigate their performance during real operational conditions and to evaluate how the alarm threshold settings could be optimised.

9.2 Hollandia Seaways (DFDS ro-ro cargo ship)

Hollandia Seaways (IMO: 9832585) is a ro-ro cargo ship which was built in 2019 and is sailing under the flag of Denmark for the Danish international shipping and logistics company DFDS [47]. The ship travels between the ports of Vlaardingen (Netherlands) and Immingham (UK) on a daily basis and has an overall length (LOA) of 235 meters, a breadth of 33 meters, and a cargo carrying capacity of 60500 gross tonnage or 6700 gross lanemeters, which is equivalent to ~449 DFDS trailers [48]. Figure 33 shows a photo of the ship.

Figure 33. A photo of Hollandia Seaways [49].

9.3 Installations and initial testing

The candidate detectors for the operational trial were installed on Hollandia Seaways with a view to the aft weather deck as shown in Figures 34 and 35. A list of the installed detectors is also presented in Table 13. The installations included two thermal imaging detectors, a video flame detector, three flame wavelength detectors (two IR3 and one IR array), and a hybrid detector which combined video fire analytics with thermopile heat detection (note: a thermopile is a set of thermocouples connected in a series on a circuit to detect heat based on the thermoelectric effect [50], and as such, a thermopile sensor is less sensitive compared to microbolometers used in thermal imaging cameras for infrared radiometry). All the detectors were configured using their default medium sensitivity settings. After installation, the detectors were tested using a flare with flames which was detected within a few seconds (see example footage snapshot in Figure 36).

Figure 34: LASH FIRE detectors fixed on deck 11 of Hollandia Seaways with a view to deck 7, i.e., the aft weather deck (highlighted in the bottom figure from [51]). Table 13 lists the detectors, which were on board from Feb 2022 until July 2023.

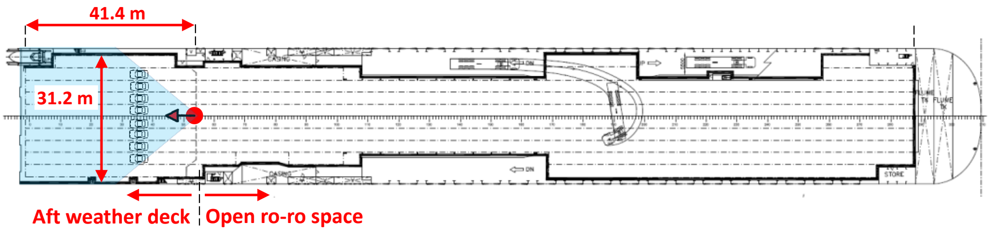


Figure 35: Location of detector installations on deck 7 of Hollandia Seaways for the operational trial of LASH FIRE. The blue shade indicates the general area of coverage offered by the detectors. The detector types are listed in Table 13.

Table 13: Optical detector installations on Hollandia Seaways with a view to the aft weather deck for an operational trial.

ID	Detector
FD1	Triple-IR flame wavelength detector 1
FD2	Triple-IR flame wavelength detector 2
FD3	IR array flame wavelength detector (16x16 IR3 sensors)
VFD1*	Video flame detector
IR1	IR thermal imaging camera 1
IR2	IR thermal imaging camera 2
H1	hybrid detector (video fire analytics with thermopile heat detection)

* VFD1 was a detector unit with video analytics for flame detection, which was different from the video analytics software tested on the closed deck using a regular CCTV camera.

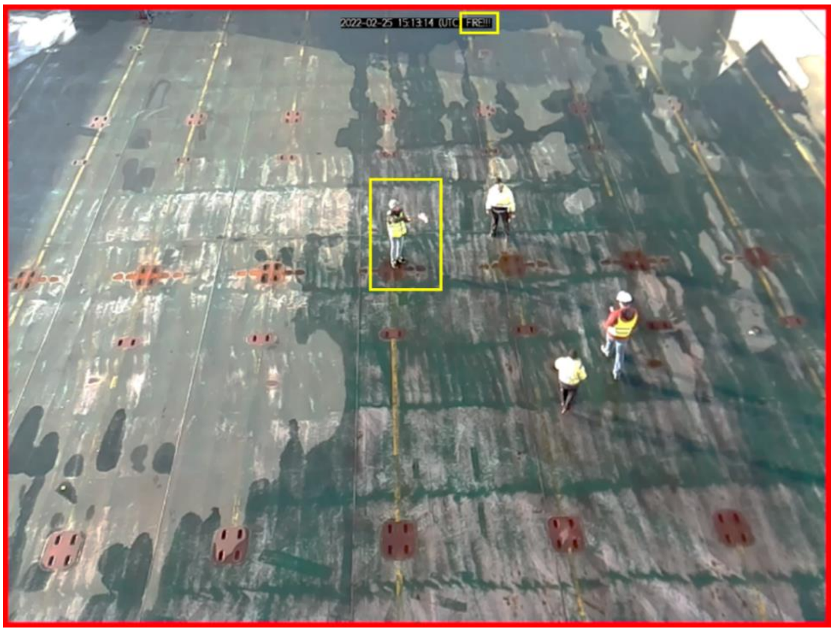


Figure 36: Snapshot from footage recorded by the built-in camera of the triple-IR flame wavelength detector on the aft weather deck as the flame is detected during the initial testing within seconds. The person holding the flare and the "fire" message have been highlighted manually for clarification.

9.4 Nuisance alarms during normal operations on board

Table 14 shows the history of nuisance fire alarms from the LASH FIRE detectors installed on Hollandia Seaways for the period from February 2022 to July 2023 while the ship operated as usual. Note that although a low number of nuisance alarms is considered beneficial, the performance of the systems cannot be judged solely based on these results, because a low number of nuisance alarms might be linked to a low sensitivity and thus less ability to detect a real fire.

No real fires occurred during the operational trial, and the flame wavelength detectors had no nuisance alarms during the normal operations, but the other detection systems did have some nuisance alarms (see Table 14). In the case of the video flame detector on the weather deck, the history of alarms was not recorded in the control panel other than the alarms generated during the initial flare testing. This was due to an error in the installation of the system which was discovered during the final fire tests where the detector was observed to detect the fire (based on LED on the device) while no record of the alarms was available in the control panel. The hybrid detector produced a few nuisance alarms. No photos were available from the related alarm incidents, but they are usually expected to be due to the light conditions in the open environment as well as camera flare or saturation due to sun reflections.

Table 14: History of nuisance fire alarms from the new systems installed on Hollandia Seaways as part of LASH FIRE.

	Thermal cameras		**Hybrid (video + thermopile)**	**Video flame detector**	**Flame wavelength detectors**		
	IR1	**IR2[1]**	**H1**	**VFD1[2]**	**FD1**	**FD2**	**FD3**
Feb 2022	0	3	0	-	0	0	0
March	4	4	2	-	0	0	0
April	3	5	3	-	0	0	0
May	9	22	0	-	0	0	0
June	0	2	1	-	0	0	0
July	5	0	0	-	0	0	0
Aug	1	0	0	-	0	0	0
Sept	0	0	0	-	0	0	0
Oct	0	4	0	-	0	0	0
Nov	0	1	0	-	0	0	0
Dec	0	1	0	-	0	0	0
Jan 2023	0	3	0	-	0	0	0
Feb	0	2	0	-	0	0	0
March	0	2	0	-	0	0	0
April	0	1	1	-	0	0	0
May	0	6	0	-	0	0	0
June	0	6	0	-	0	0	0
July 2023	0	2	0	-	0	0	0

1 Camera IR2 first had a detection temperature threshold of 90°C. On May 31, 2022, this was raised to 160°C, and a 20-s delay was added.
2 The video flame detector on the weather deck produced no record of alarms in the control panel.

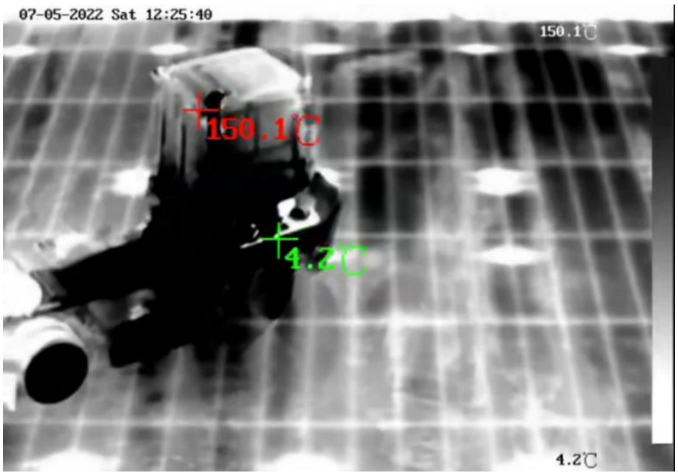


Figure 37: Example nuisance alarm source identified by the thermal imaging detection system on the weather deck: the exhaust pipe of a truck with a temperature of ~150°C has been detected as a potential fire source.

Nuisance alarms were triggered frequently by the thermal imaging cameras, namely, due to the exhaust pipes of vehicles (example shown in Figure 37). This includes the muffler and the tailpipe of the vehicles' exhaust system, which have operational temperatures ranging from 150°C to 310°C [52], [53], while performance vehicles may have exhaust pipes at average temperatures ranging from 430°C to 540°C [54]. This makes the hot exhaust pipes very hard to avoid using thermal imaging detectors as they rely on the detection of heat based on much lower thresholds of temperature, in some case as low as 70°C. For thermal imaging camera IR2, the threshold was raised from 90°C to 160°C several months into the trial (May 31, 2023), with the addition of a 20-s delay for detection. However, there were still frequent alarms from this camera subsequently. As opposed to thermal camera IR2 which had regular nuisance alarms throughout the trial despite changing its settings, thermal camera IR1 had 22 alarms within the first 7 months and no alarms during the next 11 months, while no changes were made to its default detection settings (which considered alarms for hotspots beyond 90°C with a short delay, excluding vehicle surfaces identified by the algorithm described in section 8.2.2). Therefore, it is likely that some nuisance alarms will always be generated from the hot exhaust pipes of vehicles despite the alarm settings. This reduces the reliability of thermal imaging detectors for *systematic* fire detection. However, the *manual* use of these systems is still expected to be highly beneficial and effective for fire confirmation and localisation, i.e., operators can use these detection systems for the surveillance of hotspots without connecting the camera(s) to the control panel for fire alarms [2].

9.5 Other operational observations

One of the operational challenges observed during the LASH FIRE trial was that some camera mounts got loose after two months (see Figure 38), such that they had to be adjusted upright by tightening the bolts in the mount. This happened once again for one of the said cameras after nearly a year. It is expected that the weather elements and ship vibrations contributed to the natural loosening of the connections, which highlights one of the challenges involved with the use of detectors for weather deck environments as well as the need for a robust design of their connection against tilting.

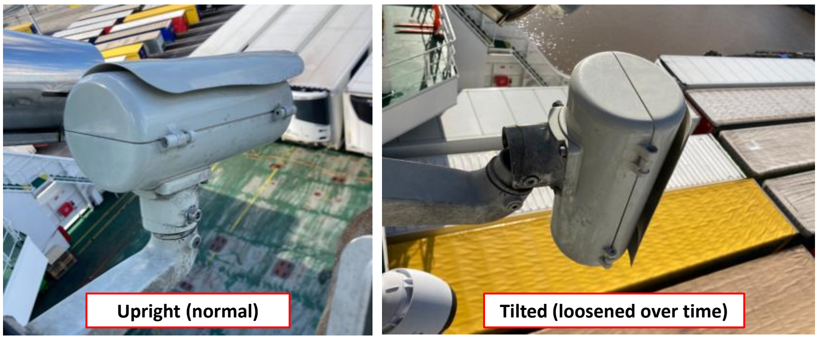


Figure 38: Camera tilting observed due to the connections getting loose over time.

Figure 39: LASH FIRE box on board Hollandia Seaways containing a standalone fire alarm panel, draw-out monitor and keyboard, several computer cases, some data acquisition systems, and associated accessories.

Another challenge faced during the operational trial was that the detectors could not be connected to the ship’s main fire control panel to sound the fire alarm on board, because many nuisance alarms were expected which were not welcome. Instead, a standalone fire control panel was used for the purpose of the operational trial (see Figure 39). The used control panel allowed for only one active alarm for each detection system, i.e., if an alarm was triggered by detection system ‘A’, a new alarm could not be triggered from system ‘A’ until its previous alarm was manually dismissed (which was done daily via remote access to the system). Due to this limitation, the active alarms had to be muted as soon as they appeared so that the involved systems could produce new alarms, while if the alarms were not deactivated for a certain period, it was not possible to know whether those systems with an active alarm had triggered multiple alarms during that period or just one. Moreover, one of the detection systems had a non-latching relay that produced a non-stop alarm signal, i.e., an alarm from this system could not be dismissed manually on the fire control panel. Dismissing the persisting alarm from this detection system was only possible through its dedicated software installed on a separate computer connected to the detector. This made it difficult to centralise the control over the fire alarms from different systems. Nevertheless, it is expected that the deactivation of the alarms would have been easier if the systems had been integrated into the ship's fire alarm panel monitored regularly by the ship's operators, such that the limitation regarding the active alarms may not be a big issue.

9.6 Final fire experiments on the weather deck

9.6.1 Setup

At the end of the operational trial, several fire experiments were conducted on board using the propane burner shown in Figure 21 with the heat output shown in Figure 23 by placing it at several different locations as shown in Figure 40. This was done to challenge the weather deck detectors in terms of both on-axis and off-axis detection performance at different distances.

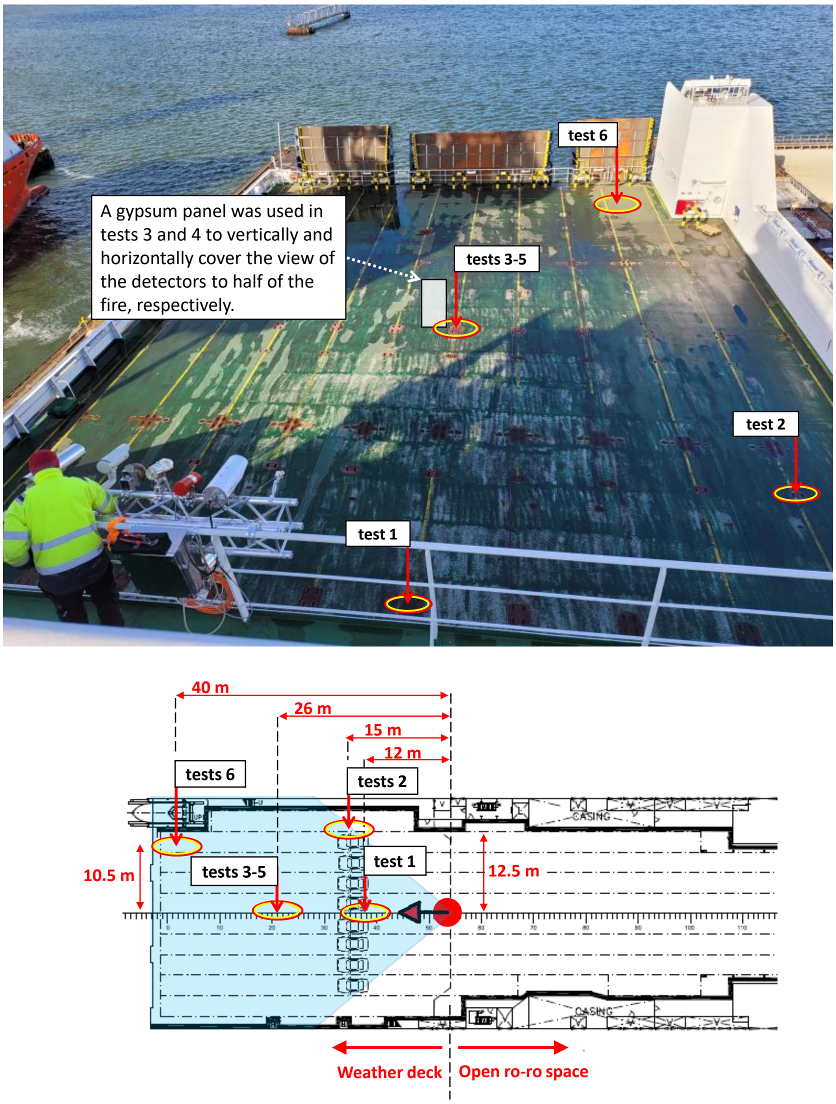


Figure 40: Setup and scenarios of fire experiments on the aft weather deck of Hollandia Seaways.

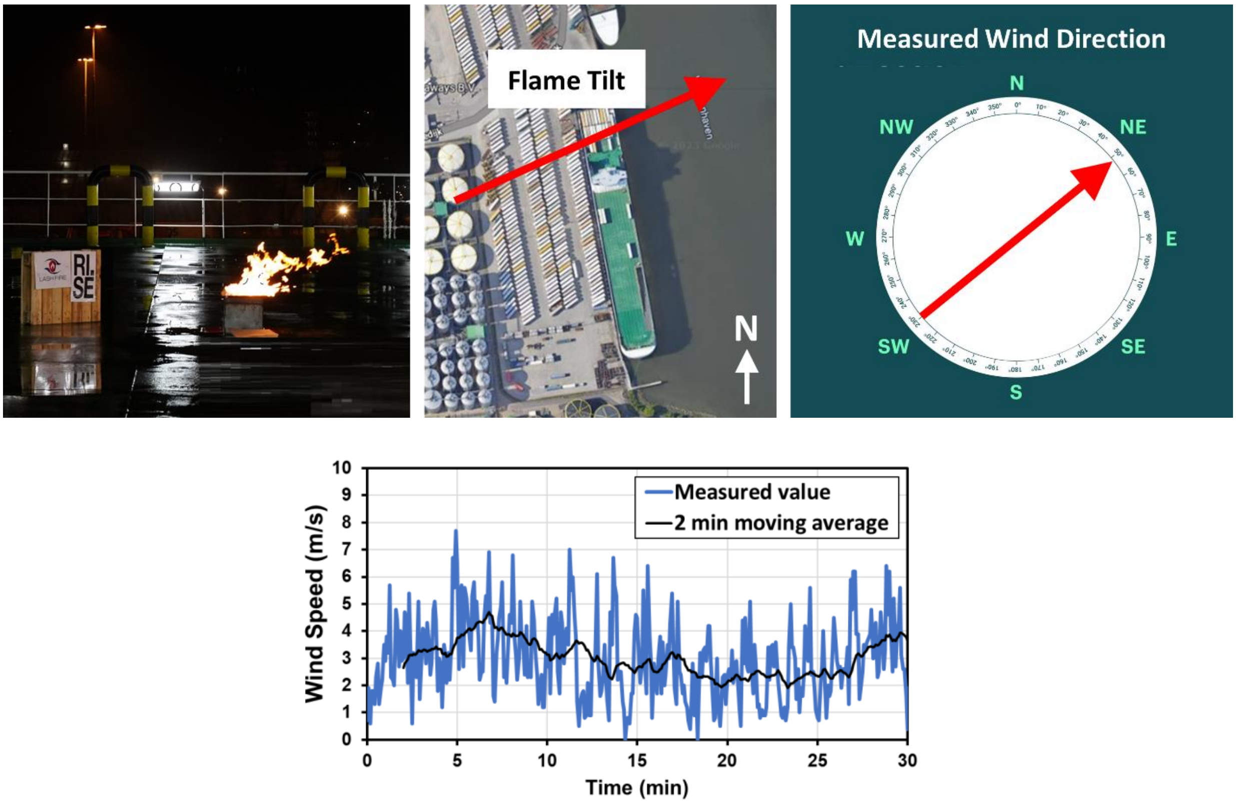


Figure 41: Flame tilt observations versus wind measurements made using a portable probe in the middle of the weather deck in the aft part of Hollandia Seaways during onboard fire experiments.

The ship was available for experiments at night-time, while the ambient temperature was 10°C and the relative humidity level was between 75 and 100%. According to the ship's control room, there was crosswind blowing against the ship at the time of the experiments with a velocity in the order of 13 m/s. This is while the local wind velocities in the test area on the weather deck were in the order of 2 to 4 m/s on average according to the measurements made using a portable probe (wind data shown in Figure 41 along with the direction of flame tilt).

It is expected that the detectors were significantly challenged during the onboard experiments compared to how they are usually tested according to the European standard EN 54-10 [26]. Based on the requirements of EN 54-10 [26], the fire performance of optical flame detectors should be examined through the detection of a fire tray (including firstly heptane and then a methylated spirit) which must be achieved within 30 s for eight identical detectors arranged on a line at a height of 1.5 m and a horizontal distance of 25 m from the fire for a rating class 1, a horizontal distance of 17 m for a rating class 2, and a horizontal distance of 12 m for a rating class 3. For the LASH FIRE experiments on board Hollandia Seaways, the propane burner served as the fire tray (see equivalency discussed in section 8.3), and the horizontal distances ranged from 12 m to 40 m (i.e., farthest distance on the deck), while the height of the detectors was 15.7 m (fixed on deck 11). The off-axis angle (i.e., angle with respect to the optical axis of each detector) ranged from 0 to 46 degrees along the horizontal plane during the onboard experiments, allowing to evaluate the directional dependence of detection, which has its dedicated test procedure in EN 54-10 as well [26].

9.6.2 Results

Table 15 provides a summary of the results of the weather deck experiments in terms of the detection times obtained for the different detectors. These results indicate that the systems managed to detect the fire like they did in the laboratory experiments, with only four cases of no detection, namely, one associated with thermal camera IR2 for a fire position which was at the very bottom of its field of view, two associated with hybrid camera H1 for the farthest off-axis fire position, and lastly, one associated with the video flame detector VFD1 when the top half of the flame was obstructed. Given that a single detector is usually not expected to cover the entire deck, it is considered acceptable to see such limitations and detection failures at the borders of field of view of detectors IR2 and H1, such that their results can be considered highly promising. The lack of detection for the obstructed flame by VFD1, however, is a discouraging weakness of video analytics relying on flame flicker patterns which are not easily identifiable for obstructed flames.

Table 15: Detection time of detectors (in seconds) during weather deck experiments on board Hollandia Seaways. The detector IDs are explained in Table 13. 'ND' indicates 'No Detection', i.e., the detector did not detect the fire after several minutes. 'Yes' indicates detection happened while the timing was not recordable. 'Fault' means the detector unit's LED was indicating a fault in the system. IR1 and IR2 are simply infrared thermal cameras 1 and 2, and there is no difference in their technology.

					Flame wavelength detectors			**Video flame detection**	**Thermal imaging cameras**		**Hybrid (video + thermopile)**
Test no	**Ignition position**	**Horizontal distance to fire (m)**	**Off-axis angle (degrees)**	**Obstruction of view to flame**	**FD1**	**FD2**	**FD3**	**VFD1**	**IR1**	**IR2**	**H1**
1	Center 1	12	46	None	7	Yes	Yes	Yes	2	ND	8
2	Off-axis 1	15	40	None	5	Yes	Yes	Yes	128	201	15
3	Center 2	26	0	None	7	46	Yes/Fault	Yes	2	22	11
4	Center 2	26	0	Left 50%	7	Yes	Yes/Fault	Yes	3	23	14
5	Center 2	26	0	Top 50%	7	Yes	Yes/Fault	ND	2	46	10
6	Off-axis 2	40	17	None	8	Yes	Yes/Fault	Yes	7	ND	ND

Considering the results of detection time, flame wavelength detector FD1 offered the most reliable results, as it detected all the fires consistently within 5 to 8 s, while it did not have any nuisance alarms during the operational trial (see corresponding FD1 results in Tables 14 and 15). This is while the most sensitive detection system during the fire experiments was thermal imaging detector IR1, although this system took a long time to detect the off-axis fire during test 2, and it generated nuisance alarms for several months during the operational trial (see IR1 results in Table 14).

A challenge encountered during the fire experiments was that flame wavelength detector FD3 maintained a fire alarm status in the control panel while it did not allow recording alarms for FD3 or FD2 into the history of fire alarms in the control panel. It is expected that this was due to an error in the combined installation of these detectors, as FD3's LED was lit with a yellow colour, which indicated a fault mode according to the instruction manual of this detector. When not in a fault mode, FD3's LED was lit with a red colour during the fire experiments, which indicated that the detector was detecting a fire.

The visual information provided by the LED that is physically located on the detector unit itself is therefore expected to be highly useful, especially in situations where there is a fault in the connection between the detector and the fire alarm panel. Firstly, if the detector's LED is indicating a fire, it could help the crew confirm and localise the fire within the area covered by the detector. Secondly, in situations where there is a fault in the system, the crew can investigate the problem and respond accordingly. This is in addition to the requirement that such connection faults must be visible in the fire alarm panel for the ship operators to see and fix.

9.7 Main findings from onboard evaluations

During the operational evaluations of the candidate detection systems installed on Hollandia Seaways, it was found that the flame wavelength detectors offered the most reliable results, as they did not have any nuisance alarms while they detected all the fire experiments consistently within seconds, both at the onset of the operational trial and at the end of the trial period. Moreover, these detectors did not experience the gradual tilting observed for other detectors, as the flame wavelength detectors had the smallest size (diameter ranging from 50 mm to 130 mm) and smallest weight (ranging from 650 g to 4.4 kg), as opposed to IR cameras which were the largest and heaviest (3 to 20 kg depending on the housing material). In the case of thermal imaging detection systems (i.e., systems using IR cameras), frequent nuisance alarms were observed due to the hot exhaust pipes of vehicles which regularly exceeded the infrared radiation thresholds used by the thermal cameras for fire detection. As a result, it is expected that despite the adjustment of detection threshold settings within reasonable bounds, some nuisance alarms for thermal cameras will persist from the hot exhaust pipes of vehicles. This reduces the reliability of thermal imaging cameras for *systematic* fire detection. However, the *manual* use of these detection systems is still expected to be highly beneficial, i.e., operators can use thermal imaging camera installations for the surveillance of hotspots without connecting the cameras to the control panel for fire alarms. Moreover, the operational trial suggests that the detectors to be used on board ro-ro ships must be tested for progressive tilting based on regular shakes and vibrations, using the detector’s own dedicated mount and fixing accessories.

The onboard fire experiments conducted at the end of the operational trial were found to be more challenging for the systems than standard tests performed according to EN 54-10 [26]. This was due to the long distances involved, the extensive height of the detectors on the weather deck, and the large off-axis angles faced by the detectors in the ship’s geometry. First and foremost, this highlights the importance of placing enough detectors on the weather deck to cover the entire area with some overlaps. Moreover, this draws attention to the detector limitations in terms of field of view and distance ratings which are not covered by class 1 to 3 defined in EN 54-10 [26]. The experiments also revealed that the visual information provided by the LED of the detector units is highly useful, as it could help the crew confirm and localise the fire within the area covered by the detector, and the crew can investigate the problem in situations where there is a fault in the connection between the detector and the fire alarm panel.

10 Recommendations

Main author of the chapter: Davood Zeinali, FRN

As part of Risk Control Option 10 (RCO10) of LASH FIRE, the following Risk Control Measures (RCMs) were evaluated for fire detection on weather decks:

(1) Flame wavelength detectors: this RCM focuses on multi-spectrum IR flame detectors which have long-range detection capability suitable for ro-ro spaces.
(2) Thermal imaging (IR) detectors: this RCM includes detection systems that employ thermal imaging (IR) cameras.

Due to the excellent ability of thermal imaging systems to see through thin smoke (example shown in Figure 30) and their ability to identify various heat sources, developing fires, and concealed fires which are otherwise undetectable using other means (example shown in Figure 17), the *manual* use of thermal imaging fire detection systems is recommended, i.e., the ship operators are recommended to use thermal imaging camera installations for surveillance without connecting the cameras to the fire control panel (to avoid frequent nuisance alarms due to the hot exhaust pipes of vehicles). However, as highlighted in the previous chapter, flame wavelength detectors are expected to offer the most reliable results for *systematic* fire detection on weather decks and are thus the focus of this chapter regarding the recommendations for fire detection on weather decks.

Based on the results of laboratory and operational evaluations, the following recommendations can be made regarding the design and implementation of flame wavelength detectors for fire detection on weather decks:

- Flame wavelength detectors to be installed on weather decks must be multi-spectrum IR flame detectors which can distinguish radiated energy in the CO_2 emission waveband.
- The detectors must incorporate an LED light on the detector unit that can provide an alert regarding the detection of fires as well as faults in the system based on the colour of the LED light. This can help the crew to confirm and localise the fire within the area covered by the detector, and the crew can investigate the problem in situations where there is a fault in the connection between the detector and the fire alarm panel.
- The detection sensitivity of the detectors may be unacceptably lower in off-axis locations. To verify the desired sensitivity, different angles must be considered through fire tests, including upward, downward, leftward, and rightward angles as shown in Figure 42. A procedure for directional dependence evaluation is described in EN 54-10 [26] (see also explanations in section 9.6.1).
- Medium sensitivity settings and a 5-s delay are recommended for the fire alarm criteria.
- In the case of IR array detectors, certain areas of the field of view may be masked to improve performance if the system settings allow this.
- The guidance of autonomous fire monitors is recommended to be made using IR array flame wavelength detectors, as they were found to be immune to nuisance alarms on board and capable of localising the fire within their field of view with sufficient accuracy, although these detectors are expected to be temporarily desensitised by the continued presence of flames in their field of view. Therefore, the first fire detection information must be used to aim the water nozzle of the autonomous fire monitor at the fire, while later the nozzle must continue to focus on the initial spot until new fire location information becomes available from the detector.
- The detectors are recommended to be accompanied by a built-in video camera to provide live information for fire confirmation and localisation, which can be further facilitated using video analytics highlighting the boundaries of smoke and flame in the video images [2].

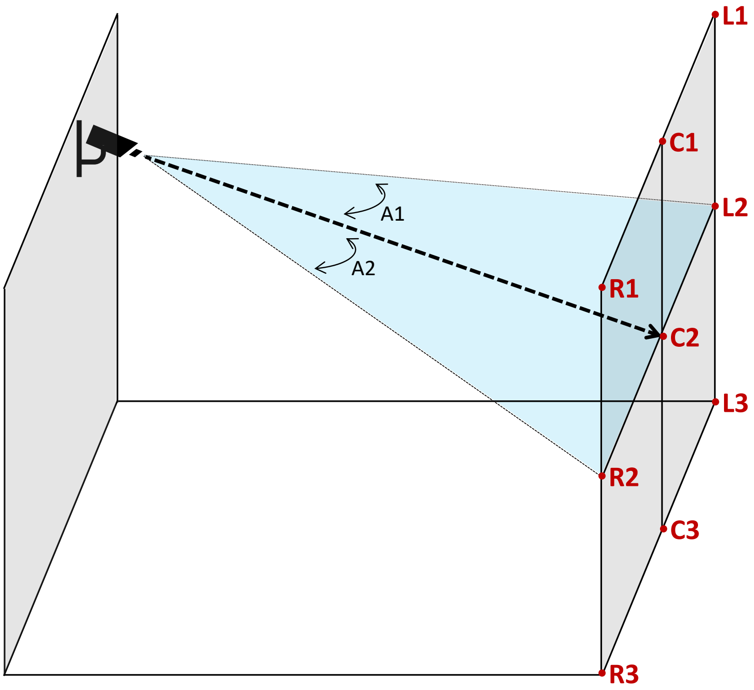


Figure 42: Test locations for detector performance evaluations on and off axis. Location C2 is on axis, i.e., the detector is directly aimed at this location. Indicated angles A1 and A2 are the degrees with which locations L2 and R2 are off axis, respectively. Accordingly, the evaluated horizontal field of view is as wide as A1+A2 degrees. The width of the evaluated vertical field of view can be quantified the same way by adding up the vertical angles tested off axis.

- Flame wavelength detectors that come with a built-in video camera do not rely on a correct orientation for their detection functionality. However, for the live footage to be useful for visual fire confirmation and localisation, the detector must be oriented correctly such that its video footage is upright. This is also important for the combination of the system with video analytics software for fire localisation.
- An important factor to consider for the mounting positions of the detectors is their accessibility for maintenance, as they need to be checked and cleaned periodically.
- Some commercial detectors come with an option for a heated lens window, which prevents frost, condensation, and ice formation on the lens window. Such a solution is highly beneficial for maintaining detection performance under cold weather conditions.
- Fuels that are not carbonaceous and do not produce carbon dioxide upon burning, e.g., hydrogen or ammonia, cannot be detected directly using IR flame wavelength detectors. However, secondary objects that catch fire due to the flames from these non-carbonaceous fuels are identifiable using IR flame wavelength detectors. Such flame spread is highly likely on weather decks because the space is tightly packed with cargo. Therefore, it is expected that IR flame wavelength detectors will be adequate for the detection of fires originating from fuels that are not carbonaceous. Nevertheless, if early detection of such flames is desired, other detectors are recommended (UV+IR flame wavelength detectors are a typical solution, although their detection range is short, and they are less immune to nuisance alarms).

11 Conclusion

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LASH FIRE action 9A was aimed at providing quicker and more reliable fire detection on weather decks through the evaluation of new and advancing technologies. This task essentially found optical detectors to be the most practical solution capable of dealing with the harsh conditions of the weather decks and their lack of a deckhead. Based on the evaluations performed through action 9A, it is recommended to implement multi-spectrum IR flame wavelength detectors as a reliable means of fire detection on weather decks.

Multi-spectrum IR flame wavelength detectors offered optimal operational results on the weather deck, as they did not have any nuisance alarms while they detected all the fire experiments within seconds. The tested detectors also provided live video which was found to be highly useful for fire confirmation and localisation. Flame wavelength detectors are also approved by classification societies and marine codes, and they are currently used in shipboard machinery spaces to monitor engines. Versions with optional HD ONVIF video cameras can integrate with most IP CCTV video management systems, and they are helpful for post fire analysis of recorded video. The multi-spectrum IR flame wavelength detectors offer a large coverage area, but they require a free line of sight for their operation. Therefore, it is recommended to use multiple detectors to provide adequate coverage over the weather deck area.

Due to the excellent ability of thermal imaging systems to see through thin smoke and their ability to identify various heat sources, developing fires, and concealed fires, the *manual* use of thermal imaging fire detection systems is recommended, i.e., the ship operators are recommended to use thermal imaging camera installations for surveillance without connecting the cameras to the fire control panel (to avoid frequent nuisance alarms due to the hot exhaust pipes of vehicles). Hand-held devices are also expected to be useful for closer examinations of cargo items for signs of high temperatures by means of periodic fire patrols.

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