FIRESAFE II

Alternative fixed-fire extinguishing systems for ro-ro spaces on ships

Final Report

Version 1.2 – December 2018

BUREAU VERITAS

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Contract No.:	2017/EMSA/OP/17/2017
Project Name:	Second study investigating cost-efficient measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE II)
WP:	Part 3: Alternative fixed fire-extinguishing systems on ro-ro spaces
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Rev.	Date	Author(s)	Reason for issue
0	13/06/2018	See list of authors	Interim report – Deliverable
0.1	06/07/2018		Revised interim report after comments by EMSA
1.0	08/11/2018		Final draft for internal review
1.1	16/11/2018		Final report sent to EMSA
1.2	19/12/2018		Revisions after receiving comments from EMSA

1 ABSTRACT

The effectiveness of ‘drencher systems’ per Resolution A.123(V) has been questioned for many years. This report presents a review of potential commercially available alternative systems and their expected performance efficiency, water consumption and estimated installation costs. Additionally, large-scale fire tests were performed for selected systems.

Three main alternative fire-extinguishing systems were identified:

- Compressed Air Foam Systems (CAFS)
- Foam-water sprinkler and foam-water spray systems; and
- Water curtains.

Water curtains was the least expensive system, but the areas sub-divided by the water curtains require cargo spacing, resulting in significant yearly losses in income for a ship owner. Furthermore, water curtains were de-selected since they cannot replace a conventional fire-extinguishing system.

The installation cost for the selected CAFS was very high and it gave limited fire suppression in the large-scale fire tests, probably due to the limited discharge density of 2.4 mm/min.

The system per MSC.1/Circ.1430 (10 mm/min) had superior performance while the system per Resolution A.123(V) (5 mm/min) and the foam-water spray system (6.5 mm/min + foam) limited the fire size to some degrees. However, for a potential spill fire scenario, improvements of foam could be relevant.

Foam injection could be an alternative, but no new system was recommended to be required.

2 EXECUTIVE SUMMARY

The main objective of Part 3 of the FIRESAFE II study was to identify alternative, commercially available fixed fire-extinguishing systems having the potential to be used for ro-ro spaces on ro-ro passenger ships and then estimate their performance effectiveness in terms of fire extinguishment, fire suppression and fire containment as well as water consumption and expected installation cost on new-built and existing ships. It was specifically requested that “water curtains” should be one of the alternative systems to be studied. The study did also address new fire hazards associated with alternative fuel vehicles as cargo.

The following fire-extinguishing systems recognized in SOLAS were identified:

1. Manually activated water spray systems as per Resolution A.123(V).
2. Automatic sprinkler or deluge water spray systems as per MSC.1/Circ.1430.
3. Automatic nozzle or deluge water mist systems as per MSC.1/Circ.1430.
4. High-expansion foam systems as per the FSS Code.
5. Gas fire-extinguishing systems as per the FSS Code.

The following three feasible alternative fire-extinguishing systems were identified:

1. Compressed Air Foam Systems (CAFS).
2. Foam-water sprinkler and foam-water spray systems.
3. Water curtains.

These three systems were evaluated theoretically, where the fixed-pipe CAF system was theoretically judged to offer several benefits compared to traditional foam-water sprinkler and foam-water spray systems, for example an improved penetration of the fire plume, a better fuel-vapor barrier and longer burn-back time for flammable liquid spill fires, better thermal radiation protection as the foam blanket stays in place for extended periods of time on top of a fuel and sticks to vertical surfaces, and a reduction of the quantity of water and foam concentrate. However, the literature survey did not identify any direct fire test data for the ro-ro space application that supports how a CAF system should be designed and installed.

A foam-water sprinkler or foam-water spray system would improve the performance against flammable liquid spill fires as compared to a traditional water spray deluge system. The use of a foam agent additive may also have some benefits for solid combustible fires, as it blocks heat radiation which prevents or limits fire spread.

Limited test data is available for water curtains. The available test data indicated that water curtains may be used to sub-divide a space by limiting the heat radiation and cooling the hot combustion gases. However, the available test data showed that water flow rates in total probably need to be high. Furthermore, if used for a ro-ro space, water curtains need to be supplemented by any of the other fire-extinguishing systems discussed in the report in order to control, suppress or extinguish a fire.

The installation costs for the systems was estimated based in input from system suppliers. The results indicated that CAFS is the most expensive of the three alternative systems. A system with water curtains was estimated to be the least expensive, but the areas sub-divided by the water curtains require a “firebreak”, i.e. a horizontal spacing of the cargo. This spacing results in additional costs due to reduced income, associated with significant yearly losses for a ship owner.

CAFS and foam-water sprinkler/spray are commercially available but not recognized for the protection of ro-ro spaces. Water curtains are not commercially available and there is no established installation or testing standards for such system. Furthermore, water curtains were not considered possible to replace a conventional fixed fire-extinguishing system in ro-ro spaces, and this solution would be more suitable for sub-division and containment than extinguishment. Water curtains were therefore not selected for testing.

Two alternative fire-extinguishing systems were selected for large-scale fire tests: a foam-water spray system and a CAFS. The fire suppression performance of the two systems was compared to the performance of a deluge water spray systems designed in accordance with Resolution A.123(V) and a system designed in accordance with MSC.1/Circ.1430. The former is commonly used on existing ships, while the latter is used on ships constructed after 2012. The fire scenario used in the tests simulated a partly shielded (to the water spray) and partly exposed fire in a freight truck trailer. It was concluded that the deluge water spray system designed in accordance with MSC.1/Circ.1430, discharging 10 mm/min of plain water, had a superior performance than all of the other systems tested. A discharge density of 5 mm/min, associated with the system designed in accordance with Resolution A.123(V), limited the fire but not to a degree where fire spread to a space above or to adjacent cargo could definitely be judged to be prevented. The foam-water spray system had a discharge density of 6.5 mm/min and the performance was more or less between the two water spray systems. The improvement compared to the system designed in accordance with Resolution A.123(V) were likely mainly due to the increased discharge rate and there were limited signs of performance improvements due to the use of the foam additive. However, for a potential fire scenario that also involves a spill fire, improvements of using foam could be relevant. The CAF system tests were terminated since only limited fire suppression was observed. Part of the reason for the relatively poor performance of the system is probably that the discharge density of 2.4 mm/min was significantly less compared to that of the other systems.

Areas for future research include testing of the activation of automatic sprinklers or nozzles (i.e. sprinklers or nozzles that are activated by the heat from a fire) at the underside of 'obstructed ceiling constructions', revision of the fire test procedures in MSC.1/Circ.1430, testing of any scrubbing effects by sprinkler water sprays on Hydrogen fluoride (HF) generated in fires involving Li-ion batteries, and additional research on the application of high-expansion foam systems, especially inside-air systems.

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6 INTRODUCTION

Below the scope and objectives of this part of the FIRESAFE II study are outlined, followed by a brief background and a description of the methodology used. As a more detailed background, the development of MSC.1/Circ.1430 is then further elaborated.

6.1 Scope and objectives

The main objective of the study described in this report was to identify (in a literature survey) alternative, commercially available fixed fire-extinguishing systems having the potential to be used for ro-ro spaces on ro-ro passenger ships and then estimate their performance effectiveness in terms of fire extinguishment, fire suppression and fire containment as well as water consumption and expected installation cost on new-built and existing ships. It was specifically requested that "water curtains" should be one of the alternative systems to be studied. The study did also address new fire hazards associated with alternative fuel vehicles as cargo.

6.2 Background

In 2016, EMSA initiated the FIRESAFE study in order to investigate cost-efficient measures for reducing the risk from fires on ro-ro passenger ships, with a focus on Electrical Fire as ignition source as well as Fire Extinguishing Failure. These areas were considered the greatest risk contributors by the EMSA Group of Experts on fires on ro-ro decks.

The study also produced a main fire risk model covering the various stages of a fire incident on a ro-ro space of a ro-ro passenger ship, namely: ignition, detection/decision, extinguishment, containment and evacuation.

In 2017, EMSA initiated the FIRESAFE II study to investigate risk control options for mitigating the risk from fires on ro-ro spaces in relation to Detection and Decision (Part 1) as well as Containment and Evacuation (Part 2), which are items which were not specifically addressed in FIRESAFE.

In addition, based on the observation that there may be available solutions having a better efficiency than resolution A.123(V), whose cost-efficiency have not been studied, EMSA launched a specific part focusing on alternative fixed fire-extinguishing systems for ro-ro spaces on ships (Part 3, i.e. this report).

A fourth part (Part 4) focusing on detection systems in open ro-ro spaces and weather decks was also part of the FIRESAFE II study.

6.3 Methodology

In order to achieve the objective described in section 6.1, a five-step methodology was followed. Details of the steps are provided below:

- 1st step: Desk study to identify (in a literature survey) alternative, commercially available fixed fire-extinguishing systems[1] and estimate their performance effectiveness in terms of fire extinguishment, fire suppression and fire containment as well as water consumption and expected installation cost on new-built and existing ships;
- 2nd step: Selection of the system(s) expected to have the best performance in combination with a feasible cost, based on the evaluation of Step 1;
- 3rd step: Fire testing of the system(s) in order to accurately measure the expected risk reduction in relation to a conventional 'drencher' system designed and installed in accordance with Resolution A.123(V);
- 4th step: Cost-effectiveness assessment for the measured risk reduction; and
- 5th step: If relevant, development of specific proposals for rule-making.

[1] This terminology is used in SOLAS and other IMO documents, however, the terminology "fire protection systems" is broader, widely recognized and does not indicate the performance objective of the system. The latter terminology is therefore used in many international standards.

6.4 The development of MSC.1/Circ.1430

Since the mid-1990's, several projects [1,2,3] have been conducted, both aiming at investigating the fire hazards on ro-ro decks and cargo spaces, the consequences of such fires, and the most appropriate fire-extinguishing systems. The test set-up was used in a large-scale fire test, as reported in [2] and documented in a video [4]. It formed the basis for the fire test procedures in MSC/Circ. 914, adopted in 1999 for the approval of alternative fixed water-based fire-fighting systems for special category spaces. The performance criteria of these guidelines were set higher than expected from a system designed in accordance with Resolution A.123(V) and automatic activation was envisioned. The influence of ventilation conditions has been investigated in model-scale [5]. These tests showed that a fire on a ro-ro space can be very large before it becomes ventilation controlled, due to the large volumes and a virtually unlimited availability of air. A fire during loading or unloading may be critical as a fire potentially could become very large before being controlled by ventilation conditions.

With the introduction of MSC.1/Circ.1272 [6] in 2008, alternative systems were allowed to be automatically activated. These guidelines provided a performance-based fire test method for the approval of "fixed water-based fire-fighting systems for ro-ro spaces and special category spaces equivalent to that referred to in Resolution A.123(V)". The intent of the fire test procedures was to demonstrate performance with water spray systems designed in accordance with Resolution A.123(V). The fire test procedures, including the fire test set-ups and acceptance criteria, were established in a project conducted at VTT Technical Research Centre of Finland in 2006 [7]. Benchmark fire suppression tests were conducted with a water spray system designed in accordance with Resolution A.123(V), but the acceptance criteria were chosen such that they were somewhat higher than established with the benchmark system. In addition, the approach of installing automatic sprinkler systems on vehicle decks was investigated.

At the IMO, questions were raised by Member States as to whether a water spray system in accordance with Resolution A.123(V) can control or suppress a fire in the ro-ro space of a ship with modern cars, coaches and heavy goods vehicles [8,9], due the high fire load, the potential shielding of a fire and the fact that the systems are manually operated. Research conducted in Sweden in the IMPRO-project [10,11,12,13], along with several serious ro-ro fires, showed that the water spray system design based on resolution A.123(V), needed improvement. Proposed design and installation guidelines for automatic sprinkler and deluge water spray systems were submitted to the relevant IMO Correspondence Group by Sweden.

The relevant Working Group at FP55 concluded that these guidelines should be combined with the performance guidelines in MSC.1/Circ.1272 for alternative systems, to provide for a prescriptive as well as a performance-based option. The working group considered that existing fixed fire protection systems for special category spaces, approved and installed based on Resolution A.123(V), should be permitted to remain in service if they are serviceable. In May 2012, MSC 90 adopted the revised guidelines as MSC.1/Circ.1430.

However, concerns related to the performance-based option have been raised [14] as the guidelines in MSC.1/Circ.1430 set a performance level of alternative systems that is only similar or slightly better than the performance of systems that used to be installed in accordance with IMO Resolution A.123(V).

7 REVIEW OF REGULATIONS

The present review aims to give an overview of fixed fire-extinguishing system requirements applicable for vehicle spaces, ro-ro spaces and special category spaces. Specific details (relevant for this literature study) related to the design and installation of the systems considered are given later in the report and are not discussed in this section.

7.1 Reference documents

This section aims to give an overview of relevant regulations. It is to be noted that the review is based on the currently applicable regulations. Therefore, some of the requirements detailed below may not be applicable to old ships.

As a general remark, there are very few specific requirements related to fixed fire-extinguishing systems in Classification Rules. This topic is mainly covered by IMO Regulations and a few IACS texts. Therefore, this section is mainly based on the IMO and IACS documents listed in Table 1.

Table 1: List of documents used for the review of regulations of fire-extinguishing system requirements applicable in ro-ro spaces of ro-ro passenger ships.

IMO Documents	Safety of Life at Sea (SOLAS) Convention, as amended in 2017
	Fire Safety Systems (FSS) Code, as amended in 2016
	Resolution A.123(V) – Recommendation on fixed fire extinguishing systems for special category spaces, October 26, 1967
	MSC/Circ.670 – Guidelines for the performance and testing criteria and surveys of high-expansion foam concentrates for fixed fire-extinguishing systems, January 5, 1995
	MSC/Circ.798 – Guidelines for performance and testing criteria and surveys of medium-expansion concentrates for fire-extinguishing systems, June 9, 1997
	MSC/Circ.914 – Guidelines for the approval of alternative fixed water-based fire-fighting systems for special category spaces, June 4, 1999
	MSC/Circ.1165 – Revised Guidelines for the approval of equivalent water-based fire-extinguishing systems for machinery spaces and cargo pump-rooms, June 10, 2005
	MSC.1/Circ.1272 – Guidelines for the approval of fixed water-based fire-fighting systems for ro-ro spaces and special category spaces equivalent to that referred to in Resolution A.123(V), June 4, 2008
	MSC.1/Circ.1312/Corr.1 – Revised Guidelines for the performance and testing criteria and surveys of foam concentrates for fixed fire-extinguishing systems, November 22, 2011
	MSC.1/Circ.1320 – Guidelines for the drainage of fire-fighting water from closed vehicle and ro-ro spaces and special category spaces of passenger and cargo ships, June 11, 2009
	MSC.1/Circ.1430 – Revised guidelines for the design and approval of fixed water-based fire-fighting systems for ro-ro spaces and special category spaces, May 31, 2012
IACS Documents	UI SC17 Rev.2 - Definitions - Control Stations, November 2005
	UI SC32 Rev.2 - Fixed high expansion foam fire-extinguishing system, November 2005
Classification Rules	BV Rules for Steel Ship (NR467), as amended in January 2018

7.2 Definitions

Some relevant terms with regard to fire-extinguishment in ro-ro spaces are explained below, based on regulatory definitions.

7.2.1 *Ro-ro space, vehicle space and special category space*

Cargo spaces are spaces used for cargo, cargo oil tanks, tanks for other liquid cargo and trunks to such spaces. (SOLAS II-2/3.8)

Ro-ro spaces are a type of cargo spaces, defined accordingly (SOLAS II-2/3.41): *Ro-ro spaces are spaces not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction*.

Vehicle spaces are cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion. (SOLAS II-2/3.49)

Special category spaces are those enclosed vehicle spaces above and below the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m. (SOLAS II-2/3.46)

Special category spaces is the most common type of ro-ro space on ro-ro passenger ships.

7.2.2 *Closed ro-ro space, open ro-ro space and weather deck*

Some of the most important definitions for the current study are the definitions of closed ro-ro space, open ro-ro space and weather deck. Ro-ro spaces can be divided in these three categories depending on how they are enclosed:

- Weather deck is a deck which is completely exposed to the weather from above and from at least two sides. (SOLAS II-2/3.50)
- Open ro-ro spaces are those ro-ro spaces which are either open at both ends or have an opening at one end and are provided with adequate natural ventilation effective over their entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides. (SOLAS II-2/3.35)
- Closed ro-ro spaces are ro-ro spaces which are neither open ro-ro spaces nor weather decks. (SOLAS II-2/3.12)

SOLAS states that a weather deck is a deck which is completely exposed to weather from above and from at least two sides. IACS UI SC 86 additionally details that: "For the purposes of Reg. II-2/19 a ro-ro space fully open above and with full openings in both ends may be treated as a weather deck." For practical purposes, fixed fire-extinguishing systems cannot be fitted on weather decks due to the absence of a deckhead. Therefore, this criterion is often used for a practical definition of weather decks.

It can be noted that ro-ro spaces with less than 10% side openings and/or one open end are considered closed, even though such a space can have significant openings. Furthermore, one deck can include several categories of ro-ro spaces and the border between for example weather deck and closed ro-ro space can in practice be vague.

7.2.3 *Fire control*

A commonly used definition [15] of "fire control" for water-based fire protection systems is as follows: *Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.*

7.2.4 *Fire suppression*

A commonly used definition [15] of "fire suppression" for water-based fire protection systems is as follows: *Sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface.*

7.2.5 *Fire extinguishment*

A commonly used definition [15] of "fire extinguishment" is as follows: *The complete suppression of a fire until there are no burning combustibles.*

7.3 Requirements

The main requirements with regard to fire-extinguishment in ro-ro spaces are defined below.

7.3.1 *Fire-extinguishing system alternatives*

SOLAS II-2, Part G, Regulation 20, paragraph 6.1.1 requires that:

*Vehicle spaces and ro-ro spaces, **which are not special category spaces** and are capable of being sealed from a location outside of the cargo spaces, shall be fitted with one of the following fixed fire-extinguishing systems:*

- a fixed gas fire-extinguishing system
- a fixed high-expansion foam fire-extinguishing system complying
- a fixed water-based fire-fighting system for ro-ro spaces and special category spaces

SOLAS II-2, Part G, Regulation 20, paragraph 6.1.2 requires that:

*Vehicle spaces and ro-ro spaces **not capable of being sealed** and **special category spaces** shall be fitted with a fixed water-based fire-fighting system for ro-ro spaces and special category spaces, which shall protect all parts of any deck and vehicle platform in such spaces.*

Such a water-based fire-fighting system shall have:

- a pressure gauge on the valve manifold
- clear marking on each manifold valve indicating the spaces served
- instructions for maintenance and operation located in the valve room
- a sufficient number of drainage valves to ensure complete drainage of the system.

SOLAS II-2, Part G, Regulation 20, paragraph 6.1.3 requires that:

The Administration may permit the use of any other fixed fire-extinguishing system that has been shown, by a full-scale test in conditions simulating a flowing petrol fire in a vehicle space or a ro-ro space, to be not less effective in controlling fires likely to occur in such a space.

Chapter 1 of the FSS Code, paragraph 4 requires that:

The use of a fire-extinguishing medium which, in the opinion of the Administration, either by itself or under expected conditions of use gives off toxic gases, liquids and other substances in such quantities as to endanger persons shall not be permitted.

7.3.2 *Drainage and pumping arrangement*

SOLAS II-2 Part G, Regulation 20, paragraph 6.1.4 requires that:

When fixed pressure water-spraying fire-extinguishing systems are fitted, in view of the serious loss of stability which could arise due to large quantities of water accumulating on the deck or decks during the operation of the fixed pressure water-spraying system, the following arrangements shall be provided in passenger ships:

1. In the spaces above the bulkhead deck, scuppers shall be fitted so as to ensure that such water is rapidly discharged directly overboard, taking into account the guidelines developed by the Organization [MSC.1/Circ.1320];
    1. In ro-ro passenger ships, discharge valves for scuppers, fitted with positive means of closing operable from a position above the bulkhead deck in accordance with the requirements of the International Convention on Load Lines in force, shall be kept open while the ships are at sea.
    2. Any operation of valves shall be recorded in the log-book.
2. In the spaces below the bulkhead deck, the Administration may require pumping and drainage facilities to be provided additional to the requirements of regulation II-1/35-1. In such case, the drainage system shall be sized to remove no less than 125% of the combined capacity of both the water-spraying system pumps and the required number of fire hose nozzles, taking into account the guidelines developed by the Organization. The drainage system valves shall be operable from outside the protected space at a position in the vicinity of the extinguishing system controls. Bilge wells shall be of sufficient holding capacity and shall be arranged at the side shell of the ship at a distance from each other of not more than 40 m in each watertight compartment.

SOLAS II-2 Part G, Regulation 20, paragraph 6.1.5 requires that:

For closed vehicles and ro-ro spaces and special category spaces, where fixed pressure water-spraying systems are fitted, means shall be provided to prevent the blockage of drainage arrangements, taking into account the guidelines developed by the Organization [IMO Circular MSC.1/Circ.1320].

7.3.3 *Carriage of dangerous goods – water spray systems*

SOLAS II-2 Part G, Regulation 19, paragraph 3.9 requires that:

*Each **open ro-ro space having a deck above it** and each space deemed to be a closed ro-ro space not capable of being sealed shall be fitted with an approved fixed pressure water-spraying system for manual operation which shall protect all parts of any deck and vehicle platform in the space, except that the Administration may permit the use of any other fixed fire-extinguishing system that has been shown by full-scale test to be no less effective.*

However, the drainage and pumping arrangements shall be such as to prevent the build-up of free surfaces. The drainage system shall be sized to remove no less than 125% of the combined capacity of both the water-spraying system pumps and the required number of fire hose nozzles. The drainage system valves shall be operable from outside the protected space at a position in the vicinity of the extinguishing system controls.

Bilge wells shall be of sufficient holding capacity and shall be arranged at the side shell of the ship at a distance from each other of not more than 40 m in each watertight compartment. If this is not possible, the adverse effect upon stability of the added weight and free surface of water shall be taken into account to the extent deemed necessary by the Administration in its approval of the stability information.

8 FIRE HAZARDS AND FIRE SCENARIOS IN VEHICLES

The fire hazards and fire scenarios in ro-ro spaces are thoroughly discussed in some of the referenced publications in this report, but the severity of fires in modern vehicles is worthwhile to illustrate by a series of photos.

Figure 1 illustrates a fire in the front part of a freight truck. The fire involves the engine compartment, the interior of the cab, combustible exterior parts such as the side view mirrors, headlights and the bumper as well as the front tires. Melted plastics have formed a pool fire on the ground. It can also be observed that the paint is burning and that huge amounts of black smoke is formed. The convective and radiant heat from a fire like this is high and large parts of the combustible materials on fire are shielded by the body of the truck. Fire involvement of the trailer would further increase the severity of the fire.

Figure 1: Fire in the front part of a freight truck. Photo: RISE.

Figure 2 through Figure 4 show a fire inside a bus used for city traffic. The fire was intentionally started in the engine compartment and spread to the interior. The fire involved the engine compartment, the interior, combustible exterior parts and all tires. Melted plastics formed a pool fire on the ground. It can be observed that the paint is burning and that huge amounts of black smoke is formed.

Figure 2: Fire in a bus used for city traffic. The fire was intentionally started in the engine compartment. At this stage, the engine compartment is fully involved in the fire, the interior is involved, and the center part of the roof is burnt through. Photo: RISE.

Figure 3: The fully developed fire involved the complete interior and all external combustibles including the tires. The amount of black smoke from the fire was huge. Photo: RISE.

Figure 4: The remains after the test, which illustrates that all tires and the interior has been consumed. All windows and doors have broken. The body of the bus is reasonably intact, but the center part of the roof burnt through. Photo: RISE.

Figure 5 through Figure 8 illustrate heavy vehicles where staff from RISE have investigated the cause of fire. The photos illustrate the degree of involvement of different parts of the vehicles and in some cases how the fires have spread, for example from the engine compartment to the interior. For some of the vehicles, the fire has destroyed parts of their structure but in other cases the structure is relatively intact.

The application of water from over-head sprinklers or nozzles in a ro-ro space could effectively prevent the burn through of the body of a vehicle due to the cooling of water. This would make the seat of the fire almost completely shielded from the application of water. To prevent the fire from spreading to adjacent, close-by vehicles, cooling of these vehicles by the water spray is essential.

Figure 5: A fire in a bus that started in the engine compartment and spread to the interior. It can be observed that the central part of the roof has burnt through, all window glazings have broken but the rest of the structure is intact. The tires were not involved in the fire. Photo: RISE.

Figure 6: Garbage vehicle where the cab and front tires have been completely consumed in a fire, but the rear part of the vehicle was not involved as it is primarily made from steel. Photo: RISE.

Figure 7: The results of a fire in a wood chipper vehicle. It is likely that the fire started when hydraulic oil leaked and ignited on a hot surface. It can be observed that virtually all combustible materials have been consumed but the structure is relatively intact. The rear tires were installed after the fire to facilitate transport from the site where the fire occurred. Photo: RISE.

Figure 8: The result of a fire in another wood chipper vehicle that probably started in the engine compartment. It can be observed that virtually all combustible materials have been consumed but the cab is relatively intact. Photo: RISE.

Vehicles contain large amounts of both combustibles and ignition sources which when a failure occurs can cause a fire. A fire can also originate from an exterior source or arson. No matter the origin, a fire can develop rapidly and potentially cause severe problems either through general combustion products, such as heat, smoke and gas, or from other hazards connected to the heating of vehicle components. The hazards can be simplified and summarized as:

- Heat from hot gases (convective heat) and flames (radiation).
- Smoke and toxic gases.
- Fuel tank integrity loss, resulting in a fuel spill fire and a severe increase in fire size.
- Spill fires in other flammable liquids such as oils, coolants and windshield wiper fluid.
- Smaller explosions which could throw projectiles with harmful force from gas springs, airbags, tires, etc.

From a fire inside the cab, the hazards are mainly constituted by the fire growth, the produced heat and the smoke production. Such a fire is visible through the windows of the car and should come with few surprises, except the possibility of an airbag explosion which could send projectiles with a force great enough to cause severe injury. A fire starting in the passenger compartment of a car may, however, very well self-extinguish from oxygen depletion if doors and windows are closed and intact.

A fire originating in the engine compartment has fuel hoses, filters and a lot of plastic and rubber materials in its vicinity. They can provide fuel which affects the fire growth and extent. In the engine compartment and its direct surroundings, there are gas springs, airbags and other equipment which may explode and cause injuries from fragments of metal hitting personnel. A fire in the engine compartment can spread into the passenger compartment or cab and under the vehicle towards the fuel tank within a couple of minutes.

Fires in the wheel wells and around the tires may cause tire explosions which can cause injuries if a person is nearby. Exclusive rims can be produced in magnesium which when on fire would cause a violent reaction if water is applied.

Fires affecting a fuel tank can lead to a rapid fire growth when the fuel tank loses its integrity and makes the fuel available to the fire. In rare cases, fuel tanks can explode, but the main hazard comes from rapid fire growth upon integrity loss and fire spread from the resulting spill fire. Fuel tanks are designed and constructed to withstand a fire test with a two-minute exposure of flames [16]. In a real fire scenario, the time to the loss of integrity varies with the specific fire exposure, but a fuel tank will likely withstand at least two minutes of fire after the fire has started engulfing it.

The heat, smoke and toxic gases produced by the fire as well as possible small explosions and resulting projectiles are hazards to persons close to the fire and its smoke plume. The integrity loss of a tank mainly makes the fire grow, which makes it harder to control.

9 SPECIFIC HAZARDS ASSOCIATED WITH ALTERNATIVE FUEL VEHICLES

An alternative fuel vehicle is a vehicle that runs on a fuel other than traditional petroleum fuels (petrol or diesel); and also refers to any technology of powering an engine that does not involve solely petroleum (for example electric vehicles and hybrid electric vehicles).

Vehicles in general have similar equipment and therefore have similar hazards during a fire. The main differences between vehicles using different energy carriers come from the energy storage and delivery system. If the energy storage is not directly involved in the cause of the fire, the early fire growth in cars with different energy carriers will be quite similar. Some specific hazards connected to the different energy carriers are discussed below.

Except for city buses, alternative fuels are currently rarely used in vehicles used for land transportation and freight purposes. Therefore, this study does only consider passenger cars. However, in the near future, it is likely that alternative fuels will be much more common for heavy goods transportation.

9.1 Ethanol

Ethanol is very similar to the conventional energy carriers. However, a fuel spill fire could be more difficult to extinguish. Foam agents need to be alcohol resistant to perform properly. On the other hand, an ethanol spill fire may be diluted by the application of large amounts of water.

9.2 Liquefied Petroleum Gas (LPG)

For LPG cars, the fuel is pressurized to 7.5 bars. If the storage tank pressure increases above 27 bar, a pressure relief valve (PRV) opens to release the excess pressure. Some LPG cars also have temperature-controlled pressure relief device (tPRD) which activate at 110°C and release all the tank content. If they function properly in the presence of a fire they will create a jet-flame. The tPRD normally directs the released gas downwards and backwards at an angle from an outlet positioned between the rear tires. If these pressure relief devices either do not activate or if the flow through them is inadequate, the fire may cause the tank to burst and a gas explosion might follow. A fire affecting the LPG tank may cause a boiling liquid expanding vapor explosion (BLEVE).

If engulfed in flames, the activation of a PRV or tPRD is likely to occur before a conventional fuel tank loses its integrity. However, the LPG tank’s position can be better protected from the fire and therefore the time from fire start to PRV or tPRD activation may be longer.

In a pre-fire scenario where the system leaks, the dense gas may spread from the leak and ignite from a spark and cause a gas explosion.

9.3 Compressed Natural Gas (CNG)

For CNG fuelled cars, the gas is compressed to 200 bars. CNG tanks are by regulation required to be equipped with tPRD (activation temperature at 110°C) and occasionally they are also equipped with pressure regulated PRVs. If they are activated during a fire they will normally direct the gas outlet downwards and backwards at an angle from a position between the rear tires. On buses and trucks, the position and the outlet direction vary. The fire will likely ignite the gas discharge early and the released gas will burn like a jet-flame. In a fire scenario where the PRVs either do not activate early enough or if they release the gas too slow, the tank may burst, and a gas explosion might follow.

If engulfed in flames the activation of a PRV or tPRD is likely to occur before a conventional fuel tank loses its integrity. Based on test experience, a tank burst is likely to occur later. In a pre-fire scenario indoors where the system leaks, the light gas may spread from the leak and ignite from for example a spark and cause a gas explosion. If outdoors, the light gas will easily be ventilated and a gas explosion from an exterior gas cloud is unlikely.

9.4 Battery Electric Vehicles (BEV)

At present, Li-ion batteries are the most commonly used battery technology in BEV. Other technologies have been used in limited quantities and depending on the technology development their use may increase in the future. As an example, lithium metal batteries could be widely used in the future, but their main difference from the Li-ion batteries is that lithium metal should not be exposed to water, due to the metallic lithium reacting explosively in contact with water. Li-ion batteries do not contain amounts of metallic lithium high enough to achieve such a reaction. There are several different technologies and chemistries used within the Li-ion family, so the following conclusions are general and highlight the hazards rather than pointing out what technologies might be less hazardous than others in specific scenarios.

Li-ion batteries exposed to fire may be thermally provoked into a thermal runaway. In an unlikely scenario they may also start a thermal runaway due to internal short circuit either from production fault or if they have received severe mechanical damage from the outside. Such damage could be seen on the exterior, which would have to be deformed to achieve a damage to that extent. No matter how the fire started, a thermal runaway will mean that the electrolyte within the battery is decomposing in an exothermic reaction. Heat and gases are produced and if oxygen is present a fire will be ignited. Inside the battery the oxygen content is very limited, but when the pressure rises from the gas produced in the decomposition of the electrolyte it will have to be ventilated. When it is ventilated the combustible gases will burn outside the battery. There are also chemistries which produce oxygen during thermal runaway, enough to promote combustion.

A thermal runaway is difficult to stop and even though there are no visible flames, gas can still be produced and ventilated from a battery cell. If enough cooling could be provided inside the battery pack, the electrolyte decomposition could be stopped, but since the batteries are well protected from the outside it is unlikely that external cooling of the battery pack is enough. The ventilated gas composition contains toxic gases, for example Hydrogen Fluoride (HF) which is highly toxic and corrosive. It is also a quite light and volatile gas and can pass through some protective gear. Therefore, chemical suits might be needed for sufficient personal protection during fire-fighting according to guidelines from the Swedish Civil Contingencies Agency [17].

But there are also other toxic gases of concern, for example phosphorous oxyfluoride (POF_3). They are formed from the fluorine content used in the Li-ion cell, the binder (for example PVdF) and the commonly used Li-salt, hexafluorophosphate (LiPF6) [18]. The toxicity of POF3 is not known but substances similar to POF3 are highly toxic, more toxic than HF.

If engulfed in flames, a battery pack may be provoked into a thermal runaway after a time likely to exceed the time when a conventional fuel tank loses its integrity. A battery pack is also better encased and protected than a fuel tank and it could therefore take more time before the fire reaches the cells. In fire tests the results vary, but when large fires are directly exposing the battery, it has lasted for 2-11 minutes before contributing to the fire. In full vehicle tests, the first contribution has come 25-40 minutes into the fire test. Table 2 summarizes these results from references [19,20,21,22,23,24].

Table 2: Time from fire exposure to thermal runaway or electrolyte involvement in the fire.

Test conditions	Time to thermal runaway or electrolyte involvement in fire
Fire tests using flames directly on battery*	2-11 minutes
Vehicle fire tests	25-40 minutes

* In reality the battery cells would be cased and better protected. Additionally, the tests were designed to provoke a thermal runaway in a Li-ion battery, not to provide relevant information on how long a relevant fire may need to provoke a thermal runaway.

9.5 Hybrid Electric Vehicles (HEV)

At present, both Li-ion batteries and Nickel Metal Hydride (NiMH) batteries are common among HEV, but since NiMH do not burn, they do not need to be considered in this study. The HEV share characteristics both with conventional petrol fueled vehicles and BEV. However, they often have smaller petrol tanks than the conventional vehicle and smaller batteries than the BEV.

9.6 Hydrogen Fuel Cell Vehicles (HFCV)

HFCV carry hydrogen pressurized to 350 or 700 bar. They also carry Li-ion batteries. Hence, they combine hazards from both the BEV and vehicles carrying compressed gas. The batteries are of less capacity than for the BEV and likely also compared to HEV. The hydrogen is stored at higher pressure, has higher energy of combustion and is easier to ignite than CNG.

There are presently no regulations concerning fire tests on hydrogen tanks, but they can be assumed to pose similar hazards as CNG tanks. The consequences of an incident may, however, be greater.

9.7 Summary of the hazards associated with alternative fuels

Table 3 summarizes the hazards associated with vehicles, based on their fuel or the energy carrier used.

Table 3: Summary of hazards associated with fire in vehicles, based on the fuel or energy carrier used. N.A. = not applicable.

<table>
<tr><th>Hazard</th><th colspan="2">Consequence</th><th>Diesel or petrol</th><th>Ethanol</th><th>LPG</th><th>CNG</th><th>BEV</th><th>HEV</th><th>HFCV</th></tr>
<tr><td>Exposure to heat, smoke, gas</td><td colspan="2">Health hazards, fire spread, structural damage</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Smaller explosions (airbags, tires, shock absorbers, gas springs)</td><td colspan="2">Health hazards</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Liquid fuel tank loss of integrity</td><td colspan="2">Spill fire, rapid fire growth, fire spread</td><td>X</td><td>X</td><td>N.A.</td><td>N.A.</td><td>N.A.</td><td>X</td><td>N.A.</td></tr>
<tr><td rowspan="2">Gas leak</td><td>In enclosed space</td><td>In open space</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">X</td></tr>
<tr><td>Health hazards, jet flame, gas explosion flash fire, structural damage</td><td>Explosion, Flash fire, jet flame</td></tr>
<tr><td rowspan="2">Pressure relief devices (PRD) activation</td><td>In enclosed space</td><td>In open space</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2">(X)</td><td rowspan="2">(X)</td><td rowspan="2">X</td></tr>
<tr><td>Health hazards, Jet flame, flash fire, gas explosion, structural damage</td><td>Explosion, Flash fire, Jet flame</td></tr>
<tr><td>Gas tank rupture</td><td>Pressure blast, gas explosion, flash fire, structural damage</td><td>Pressure blast, gas explosion, Flash fire</td><td>N.A.</td><td>N.A.</td><td>X</td><td>X</td><td>N.A.</td><td>N.A.</td><td>X</td></tr>
<tr><td rowspan="2">Thermal runaway</td><td>In enclosed space</td><td>In open space</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">N.A.</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2">X</td></tr>
<tr><td>Health hazard, fire growth, gas explosions, structural damage</td><td>Health hazard, fire growth, gas explosions</td></tr>
</table>

Despite the specific fire hazards that were identified, the vehicle types have a lot of characteristics in common. Time is critical and limiting the damage and stopping the fire development early is important to prevent severe consequences. Preferably, a fire should be suppressed before it damages the fuel storage of the vehicle and before it spreads to an adjacent vehicle. This can be done in most fire scenarios if fire detection is early and if the right fire-fighting equipment and strategy is used. The application of water from over-head sprinklers or nozzles could prevent fire spread between vehicles, limit the fire growth rate and protect the space from heat damages as well as scrubbing the air from harmful combustion products which are caught in the water drops or react with water to form less harmful substances. Water from over-head sprinklers or nozzles may not be able to extinguish a fire inside a vehicle and if that fire affects the fuel storage there might still be severe consequences from the fire.

If the fire is affecting the fuel storage, one must be aware of the specific potential consequences of a failure of that system. The fire-fighters must not be exposed to, for example, a gas tank explosion or gases emitted from a battery in thermal runaway, unless they are sufficiently protected.

10 FIRE-EXTINGUISHING SYSTEMS RECOGNIZED IN SOLAS

The following fire-extinguishing systems recognized in SOLAS have been identified:

- Manually activated water spray systems designed and installed in accordance with the prescriptive requirements in Resolution A.123(V).
- Automatic sprinkler or deluge water spray systems designed and installed in accordance with the prescriptive requirements in MSC.1/Circ.1430.
- Automatic nozzle or deluge water mist systems tested and installed in accordance with the fire test procedures and installation guidelines in MSC.1/Circ.1430.
- High-expansion foam systems installed in accordance with the requirements in the FSS Code.
- Gas fire-extinguishing systems installed in accordance with the requirements in the FSS Code.

These systems are discussed in detail below.

10.1 Manually activated water spray systems in accordance with IMO Resolution A.123(V)

In short, manually activated water spray systems are required to be designed and installed as follows:

- The system shall be designed for a water discharge density of at least:
- 3.5 mm/min for spaces with a maximum height of 2.5 m.
- 5 mm/min for spaces with a height of more than 2.5 m.
- The system shall be divided into sections where each section should cover the entire width of the ship and at least 20 m in length.
- The pump capacity of the system shall be sufficient to ensure full discharge capacity from at least two sections (the two largest sections).
- Sectioning valves must be located outside the protected space.

Resolution A.123(V) was adopted in 1967 and the technical background data was likely based on fire tests [25] conducted in Denmark in the early 1960's, although this has not been fully verified. Systems are no longer installed based on this resolution, after the introduction of MSC.1/Circ.1430 in 2012. However, existing systems are permitted to remain in service if they are operative.

For a low-height space having a width of 30 m, a deluge system would be designed for a minimum flow rate of 4 200 litre/min. For a high-height space the corresponding system would be designed with 6 000 litre/min.

Table 4 summarizes the pros and cons of these systems.

Table 4: Pros and cons of manually activated water spray systems in accordance with IMO Resolution A.123(V).

Manually activated water spray systems designed and installed in accordance with the prescriptive requirements in Resolution A.123(V).	
Water spray systems control the fire development by wetting and cooling the fuel surface.	
Pros	**Cons**
Non-toxic and poses no environmental risk.	Problems to suppress fires that are shielded from the direct application of water.
Effective for fire involving ordinary solid combustibles.	Not as effective for flammable liquid spill fires.
Simple and reliable system.	Requires human intervention for the activation.
May be manually activated at an early stage of a fire, if the fire is detected (visually or by the fire detection system) early.	Water damage and ship stability issues.
Manual activation allows for a tactical operation of the system.	Design and installation guidelines established in the 1960's, performance may not be up-to-date.
Short-term downtime following a fire.	
Low maintenance requirements.	

10.2 Automatic sprinkler or deluge water spray systems in accordance with MSC.1/Circ.1430

As mentioned above in this report, the design and installation requirements of automatic sprinkler and deluge water spray systems were determined partly based on the results of the IMPRO-project. The project involved a comprehensive literature survey on the design and use of traditional sprinkler systems for similar fire hazards and water distribution tests as well as small-scale and intermediate-scale fire tests conducted to establish the design and installation guidelines.

With the introduction of MSC.1/Circ.1430, the possibility of using wet-, dry- or pre-action systems was offered, i.e. systems utilizing automatic sprinklers or nozzles. Automatic sprinklers are activated by the heat from a fire and water is primarily discharged over the burning area. However, systems using automatic sprinklers or nozzles are only permitted for closed ro-ro spaces, special category spaces and other spaces where wind conditions are not likely to affect system performance. Deluge systems can be applied in open ro-ro spaces when the actual wind conditions are taken into consideration, for example by using high velocity nozzles.

Table 5 shows the recommended design of different automatic sprinkler systems in spaces having a free height equal to or less than 2.5 m.

Table 5: Minimum required water discharge density and area of coverage for spaces having a free height equal to or less than 2.5 m, according to Table 4-1 of MSC.1/Circ.1430.

Type of system	Minimum water discharge density (mm/min)	Minimum coverage area
Wet-pipe system	6.5	280 m²
Dry-pipe or pre-action system	6.5	280 m²
Deluge system	5	2 × 20 m × the full breadth of the protected space

The primary advantage of wet-, dry- or pre-action systems over deluge systems is that the system typically activates earlier, and the total minimum water flow rates are considerably lower. For a low-height space having a width of 30 m, a wet-, dry- or pre-action system would be designed for a minimum flow rate of 1 820 litre/min whilst a deluge system would be designed for 6 000 litre/min. In practice, however, it is expected that fewer automatic sprinklers/nozzles would activate than those in the design area, making systems with automatic sprinklers/nozzles even more advantageous with regard to water flow rates.

Table 6 shows the design for spaces having a free height in excess of 2.5 m but less than 6.5 m.

Table 6: Minimum required water discharge density and area of coverage for spaces having a free height in excess of 2.5 m but less than 6.5 m, according to Table 4-2 of MSC.1/Circ.1430.

Type of system	Minimum water discharge density (mm/min)	Minimum coverage area
Wet-pipe system	15	280 m²
Dry-pipe or pre-action system	15	365 m²
Deluge system	10	2 × 20 m × the full breadth of the protected space

For deck heights within this range having a width of 30 m, a wet-, dry- or pre-action system would be designed for a minimum flow rate of 4 200 litre/min (wet-pipe system) or 5 475 litre/min (dry-pipe or pre-action system) whilst a deluge system would be designed for 12 000 litre/min. In practice, however, it is expected that fewer automatic sprinklers would activate than those in the design area, making systems with automatic sprinklers even more advantageous with regard to water flow rates.

An analogous calculation could be done using the design recommendations for spaces having a free height in excess of 6.5 m but less than 9.0 m, as per Table 4-3 of MSC.1/Circ.1430, but this is not given here.

Table 7 summarizes the pros and cons of these systems.

Table 7: Pros and cons for automatic sprinkler or deluge water spray systems in accordance with MSC.1/Circ.1430.

Automatic sprinkler or deluge water spray systems designed and installed in accordance with the prescriptive requirements in MSC.1/Circ.1430.	
Automatic sprinkler and water spray systems control the fire development by wetting and cooling the fuel surface.	
Pros	**Cons**
Non-toxic and poses no environmental risk.	Problems to suppress fires that are shielded from the direct application of water.
Effective for fire involving ordinary solid combustibles.	Not as effective for flammable liquid spill fires.
Reliable systems with a simple and established design.	Water damage and ship stability issues.
Short-term downtime following a fire.	High water flow rates (valid for deluge systems).
Low maintenance requirements.	Automatic activation of the system prevents the possibilities for a tactical operation, for example by initiating cooling of areas or spaces not involved in the fire.
Early activation (valid for automatic sprinklers and automatic deluge systems) for certain situations and fire scenarios (see Cons).	The may be situations or fire scenarios where the automatic activation of the system is "late" compared to manually activated systems.
Reduced water flow rates (valid for automatic wet-, dry-, or pre-action systems).	After a fire, activated automatic sprinklers or nozzles need to be replaced to put the system in service again.

10.3 Automatic nozzle or deluge water mist systems in accordance with MSC.1/Circ.1430

As mentioned above in this report, the fire test procedures for "fixed water-based fire-fighting systems for ro-ro spaces and special category spaces equivalent to that referred to in Resolution A.123(V)" was first published in MSC.1/Circ.1272 in 2008 and was later adopted in MSC.1/Circ.1430 in 2012. The acceptance criteria were chosen such that they were somewhat higher than those established with a benchmark system designed in accordance with Resolution A.123(V).

Currently, there are several approved automatic or deluge water mist systems on the market. Table 8 lists the installation parameters of two approved deluge water mist systems, a low-pressure water mist system and a high-pressure water mist system.

Table 8: Comparison of the installation parameters of two approved deluge water mist systems.

System	**Low-pressure system**	**High-pressure system**
Maximum deck height [m]	5	5
Nozzle K-factor [metric]	23	3.3
Minimum water pressure [bar]	6	80
Corresponding flow rate per nozzle [litre/minute]	56.3	29.5
Nozzle spacing [m × m]	3.5 × 3.5 (12.25 m²)	3.8 × 3.8 (14.4 m²)
Corresponding water density [mm/min]	4.6	2.0
Design area	2 × 20 m × the full breadth of the protected space	

For deck heights of 5 m and a width of 30 m, the two systems would be designed for a minimum total flow rate of 5 520 litre/minute and 2 400 litre/minute, respectively.

Table 9 lists the installation parameters of two approved automatic high-pressure water mist systems.

Table 9: Comparison of the installation parameters of two approved automatic water mist systems.

System	High-pressure system	High-pressure system
Maximum deck height [m]	5	5
Nozzle K-factor [metric]	3.1	4.2
Minimum water pressure [bar]	80	100
Corresponding flow rate per nozzle [litre/minute]	27.7	42.0
Nozzle spacing [m × m]	3.8 × 3.8 (14.4 m²)	4.0 × 4.0 (16 m²)
Corresponding water density [mm/min]	1.9	2.6
Design area	Wet-pipe system: 280 m² Dry-pipe system: 365 m².	

For a deck height of 5 m, these systems should be designed with an operating area of 280 m² if installed as a wet-pipe system and 365 m² if installed as a dry-pipe system. The corresponding, minimum total flow rates of the two systems are 532 litre/minute and 728 litre/min, respectively, in a wet-pipe system installation.

Due to reasons of installation costs, automatic systems are preferred over deluge systems and few, if any, deluge water mist systems have been installed, according to several system manufacturers that were interviewed during the literature survey. A deluge system will require a pump unit with a higher capacity as the operating area is considerably larger and the higher flow rate will increase the electrical power demand accordingly. Additionally, the system needs several deluge valves whilst a wet- or dry-pipe system could (in principle) be installed with one control and alarm valve per deck. However, one of the manufacturers that was interviewed informed that wet- or dry-pipe systems on large ro-ro spaces typically is divided into sections with about 80-90 automatic nozzles (about 30 m long sections). This is due to practical reasons: the hoistable decks can be lifted up in sections, and the piping arrangements (and also system sections) are convenient to be arranged in the same sequence. It could also be beneficial to know the location of the fire, should the crew want to check out the situation.

According to some fire-extinguishing system manufacturers that have undergone the fire tests in MSC.1/Circ.1430, it is common practice that the tests are conducted with automatic nozzles and the design and installation parameters in terms of nozzle spray angle, K-factor, operating pressure and nozzle spacing are considered acceptable also for a deluge system design. Implicitly, this means that the activation time of a deluge system should be no longer than the activation time of an automatic system.

The discharge densities for approved water mist systems range from 1.9 mm/min to 4.6 mm/min which is lower than the stipulated 5 mm/min recommended for a prescriptive deluge water spray system installed in accordance with Resolution A.123(V). This may reflect a performance improvement with water mist systems because of improved cooling capabilities and improved mobility of smaller water droplets that better can reach the partly shielded fire test source in the fire test. However, one water mist manufacturer that was interviewed during the literature survey claimed that the repeatability and reproducibility of the fire tests are poor and concluded that this may partly explain the noticeable design differences in terms of water discharge densities for the approved systems. The fire test method and the performance-based system designs resulting from the tests have been criticized [14] due to the following reasons:

- The fire test method was originally described in MSC.1/Circ.1272 and developed prior the outcome of the IMPRO-project.
- The fire scenarios are not reflecting the severity and fire load of modern real case vehicle fires.
- The performance requirements are related to the performance level of Resolution A.123(V).
- The discharge densities for currently approved systems appear to be very low.
- There is potential for the fire to overtax the water supply (relevant for automatic systems) if the fire is not suppressed, which would be likely for a shielded fire.
- There is noticeable design difference between approved systems, especially for high ceiling heights. The test reproducibility may be a concern.

It may therefore be argued that the application of approved performance-based system designs should be given with some degree of caution.

Table 10 summarizes the pros and cons of these systems.

Table 10: Pros and cons for automatic nozzle or deluge water mist systems in accordance with MSC.1/Circ.1430.

Automatic nozzle or deluge water mist systems tested and installed in accordance with the fire test procedures and installation guidelines in MSC.1/Circ.1430.	
The smaller water droplets allow the water mist to control, suppress, or extinguish fires by cooling the flame and surrounding gases, displacing oxygen by evaporation (inside an enclosed space) and attenuating radiant heat.	
Pros	**Cons**
Non-toxic and poses no environmental risk.	Water mist systems require higher water quality than traditional sprinklers.
Early activation (valid for automatic sprinklers and automatic deluge systems) for certain situations and fire scenarios (see Cons).	Performance comparable to systems in accordance with Resolution A.123(V) as per the fire test procedures.
Radiation attenuation can stop fire spread and reduce vaporization at the fuel surface.	Increased water flow rates (valid for deluge systems).
More effective than gaseous agents in case of naturally ventilated enclosures.	Higher probability for system failure as compared to traditional sprinkler systems.
Reduces temperatures and improves visibility, allowing for access to the protected compartment during fire suppression.	Automatic activation of the system prevents the possibilities for a tactical operation, for example by initiating cooling of areas or spaces not involved in the fire.
Reduced water flow rates (valid for automatic wet-, dry- or pre-action systems).	The may be situations or fire scenarios where the automatic activation of the system is “late” compared to manually activated systems.
	After a fire, activated automatic sprinklers or nozzles need to be replaced to put the system in service again.

10.4 High-expansion foam systems in accordance with the FSS Code

High-expansion foams have an expansion ratio between approximately 200 and 1000 and are suitable for enclosed spaces such as aircraft hangars, where quick filling of foam and volume fire control is required. If a large volume of foam engulfs the area being protected it will prevent air from reaching the fire, which is the primary fire extinguishing mechanism. As the foam is generated with water, and comes in contact with the fire, a large amount of water vapor is generated which helps reduce the oxygen concentration in the available air. Additionally, the water content in the foam produces a cooling effect on the fire, especially with a lower expansion ratio, which has higher water content. Foam will also isolate combustible material that has not yet caught fire. An advantage with foam is that it can spread across a fuel surface and around obstacles and fill-up volumes. High-expansion foam could also provide vapor suppression from toxic or flammable spills.

The foam generators need to be fed with fresh air from outside and high-level venting must be provided for air (including combustion gases) that is displaced by the foam. The required venting shall consist of openings, either normally open or normally closed and arranged to open automatically when the system is operated. Alternatively, exhaust fans can be used but these shall withstand high-temperature operation. It should be noted than an over-pressure inside the protected compartment is undesired as this prevents foam from entering.

High-expansion foam systems are recognized in SOLAS Chapter II-2/20 for use in vehicle, special category and ro-ro spaces. Chapter 6 - Fixed foam fire extinguishing – of the FSS Code contains specifications for fixed foam fire-extinguishing systems for the protection of machinery spaces, cargo spaces, cargo pump-rooms as well as vehicle, special category and ro-ro spaces in accordance with regulation II-2/20.6.1.3. The system shall be capable of manual release and shall be designed to produce foam at the required application rate within 1 minute of release. The system shall be capable of fire extinction and manufactured and tested to the satisfaction of the Administration based on the guidelines for the approval of fixed high-expansion foam systems in MSC.1/Circ.1271 [26] as amended by MSC.1/Circ.1384. The arrangement of the protected spaces shall be such that they may be ventilated as the space is being filled with foam. Procedures shall be provided to ensure that upper level dampers, doors and other suitable openings are kept open in case of a fire. Outside-air foam systems shall have a sufficient foam-generating capacity to ensure that the minimum design filling rate for the system is met and in addition it shall be adequate to completely fill the largest protected space within 10 minutes. However, for systems protecting vehicle spaces, ro-ro spaces and special category spaces with decks that are reasonably gas-tight and that have a deck height of 3 m or less, the filling rate shall be not less than two-thirds of the design filling rate and in addition sufficient to fill the largest protected space within 10 minutes.

High-expansion foam systems are commonly used for the protection of decks on pure car and truck carriers as an alternative to Carbon Dioxide (CO_2) systems. These systems incorporate multiple tens of large foam generators connected to vertical ducts that supplies air from the outside (top) of the vessel.

NFPA 11 recommends that the discharge rate of high-expansion foam shall be calculated in accordance with Equation 1. The draft version of prEN 13565-2:2016 [27] contains similar design recommendations.

$$\boldsymbol{R} = \left(\frac{\boldsymbol{V}}{\boldsymbol{T}} + \boldsymbol{R_S}\right) \cdot \boldsymbol{C_N} \cdot \boldsymbol{C_L} \qquad \textbf{(1)}$$

where

R = rate of foam discharge in m3/minute.

V = submergence volume in m3.

T = submergence time in minutes.

R_S = rate of foam breakdown by sprinklers in m3/minute.

C_N = compensation for normal foam shrinkage. Typically, this factor shall be set to 1.15, which is an empirical factor based on average reduction in foam quantity from solution drainage, fire, wetting of surfaces, absorbency of stock, etc.

C_L = compensation for leakage of foam from the protected compartment around doors and other openings. This factor shall not be permitted to be 1.0 even for a structure that is completely tight below the filling depth. This factor shall be permitted to be as high as 1.2 for a structure with all openings normally closed.

In NFPA 11, the maximum submergence time depends on the fire hazard and the vulnerability of the building construction. For a building that is not sprinklered, the maximum submergence time ranges from 2 minutes (for fire hazards with flammable liquids, i.e. liquids with a flash point below 38°C) to 5 minutes (for a fire hazard with ordinary combustibles). It should be noted that the maximum permitted submergence times in NFPA 11 are based on a maximum delay of 30 seconds between fire detection and foam discharge. Any delays in excess of 30 seconds shall be deducted from the recommended submergence time. The recommendations in prEN 13565-2:2016 also stress that high-expansion foam systems need to be brought into operation very quickly after the onset of fire, so suitable detection and actuation systems need to be provided as appropriate.

For a ro-ro space that involves miscellaneous fire hazards, potentially shielded fires and where the probability for rapid fire spread from one deck to another deck is high, a short submergence time is necessary.

Inside-air foam systems are relatively new high-expansion foam systems used in enclosed areas, for example, in warehouses or ships' engine rooms. These systems do not use fresh outside air for the generation of foam, but air is supplied directly from the protected compartment. Specific high-expansion foam concentrates which are resistant against combustion gases and high temperatures are therefore required. The main differences compared to conventional high-expansion foam systems are that:

- The foam is generated without the use of a fan (electric or water driven).
- No ventilation system or over-pressure openings in the protected compartment is needed.
- Positive pressure in the fire test compartment is not a concern as the air is re-circulated.
- Easier and more flexible to install the system.

Bobert [28] has undertaken a literature survey on inside-air foam systems and conducted a series of small-scale fire tests involving rack storage fires. The tests show that ventilation of the protected compartment affects the generation of foam. If the fire is under-ventilated and pyrolysis products are formed, the generation of foam decreases even if the temperature at the generator is rather low. Therefore, the size of the protected compartment and the degree of ventilation must be considered when designing a high-expansion foam using inside air. It is also essential that the system is activated early, and that the application rate is sufficiently high. The generation of foam decreased considerably when the air temperature reached 300°C.

IMO has developed guidelines for the installation, fire testing and approval of inside-air foam systems for machinery spaces and cargo pump-rooms, as contained in MSC.1/Circ.1271. However, the fire scenarios do not reflect all possible scenarios that can occur in a ro-ro space and caution should be given to applying design and installation parameters from such tests. Inside-air foam systems shall have a sufficient foam-generating capacity to ensure that the minimum design filling rate for the system is met and in addition it shall be adequate to completely fill the largest protected space within 10 minutes. However, for systems protecting vehicle spaces, ro-ro spaces and special category spaces, with spaces that are reasonably gas-tight and that have a deck height of 3 m or less, the filling rate shall be not less than two thirds of the design filling rate and in addition sufficient to fill the largest protected space within 10 minutes.

It can be argued that water damage is minimized with high-expansion foam as the water content in the foam is low. On the other hand, the most effective way of mop-up after a fire incident is by using water sprays from hose lines. It should also be regarded that high-expansion foam systems require a high level of maintenance to ensure reliable operation and they have more possible modes of failure than automatic sprinkler systems [29].

Table 11 summarizes the pros and cons of these systems.

Table 11: Pros and cons for high-expansion foam systems in accordance with the FSS Code.

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

10.5 Gas fire-extinguishing systems in accordance with the FSS Code

The design and installation of fire-extinguishing systems is provided in Chapter 5 of the FSS Code. Some of those requirements are given below.

Discharge nozzles shall be positioned such that a uniform distribution of the medium is obtained. Control valves shall be readily accessible, simple to operate and grouped together in as few locations as possible at positions not likely to be cut off by a fire in a protected space. Automatic release of fire-extinguishing medium is not permitted, except as permitted by the Administration.

Audible and visual warnings shall be given of the release of fire-extinguishing medium into any ro-ro space or other spaces in which personnel normally work or to which they have access. The pre-discharge alarm shall be automatically activated (e.g. by opening of the release cabinet door). The alarm shall operate for the length of time needed to evacuate the space, but in no case less than 20 seconds before the medium is released.

For vehicle spaces and ro-ro spaces (except special category spaces), the quantity of carbon dioxide available shall be at least sufficient to give a minimum volume of free gas equal to 45% of the gross volume of space which is capable of being sealed. At least two-thirds of the gas required for the relevant space shall be released within 10 minutes. Carbon dioxide systems shall not be used for the protection of special category spaces.

Carbon dioxide systems for the protection of ro-ro spaces and other spaces in which personnel normally work or to which they have access shall have two separate controls for releasing carbon dioxide and to ensure activation of the alarm. One control shall be used for opening the valve of the piping which transports the gas into the protected space and a second control shall be used to discharge the gas from its storage containers.

Equivalent fixed gas fire-extinguishing systems may be used for machinery spaces and cargo pump-rooms and should be designed and installed in accordance with guidelines developed by the Organization, i.e. MSC/Circ.848 (gaseous agents) and MSC/Circ.1007 (fixed aerosol fire-extinguishing systems).

Table 12 summarizes the pros and cons of these systems.

Table 12: Pros and cons for gas fire-extinguishing systems in accordance with the FSS Code.

Gas fire-extinguishing systems installed in accordance with the requirements in the FSS Code	
Gas agents are applied as total flooding agents. They extinguish fire by displacing the oxygen in the enclosed space. Eventually, this reduces the oxygen content below that which is required for combustion to take place.	
Pros	**Cons**
Inert gases like Carbon Dioxide have zero ozone depletion potential and no other environmental concerns.	Large volume of agent is required to extinguish a fire which has implications on space and weight restrictions.
Inert gases like Carbon Dioxide is not subject to thermal decomposition, meaning that they form no combustion by-products.	Rapid displacement of oxygen, high noise levels, and sometimes reduced visibility is a concern when discharged into occupied spaces.
Effective for flammable liquid spill, electrical, and ordinary Class A fires.	Safety to personnel.
	Delayed activation as automatic operation is not desired.
	Typically, ‘one-shot’ systems.
	Limited or no cooling of the space.
	Not possible to use the system for cooling or protection of adjacent spaces

11 RELEVANT ALTERNATIVE FIRE-EXTINGUISHING SYSTEMS

Three alternative fixed fire-extinguishing systems for ro-ro spaces were identified in a Workshop held in April 17, 2018 between the project partners (the list of the participants is provided in Annex A1). The first two in the list below are commercially available but not recognized for the protection of ro-ro spaces in SOLAS. The third alternative is not commercially available and there is no established installation or testing standards. Additionally, it is not a fire-extinguishing system in the sense that it could replace the current fire-extinguishing systems.

- Compressed Air Foam System (CAFS).
- Foam-water sprinkler and foam-water spray systems.
- Water curtains.

These systems are discussed in detail below. Several other systems were identified but were considered to not be possible to use in ro-ro spaces. These systems were:

- Pyrotechnically Generated Aerosols (PGA).
- Dry chemical extinguishing systems.
- Inert gas systems.

These systems are not discussed within the report due to concerns with:

- Visibility, personnel safety issues and clean-up for PGA and dry chemicals
- Personnel safety issues and compartment integrity issues for inert gases.

11.1 Compressed Air Foam Systems (CAFS)

A compressed air foam system (CAFS) releases a fire fighting foam for the extinguishment of a fire or for the protection of unaffected adjacent areas. System components of a CAFS system are typically a water source, a centrifugal pump, a foam concentrate tank, a foam proportioning and injection component, a mixing chamber or device, an air compressor, and a control system ensuring suitable mixing of the water, foam concentrate and air.

CAFS is typically used for the protection of spaces were flammable liquids are stored, handled or processed. Applications may include exposed or shielded Class B pool or spill fires and are applicable for the protection of specific hazards and equipment. Systems are typically pre-engineered and must be designed by the manufacturer for the specific application.

A CAFS is able to deliver a range of useful foam consistencies, labeled from type 1 (very dry) to type 5 (wet), which are controlled by the air-to-solution ratio and, to a lesser extent, by the foam concentrate-to-water percentage. Types 1 and 2 foams have long drain times, meaning that the bubbles do not burst and give up their water quickly, i.e. a long duration. Wet foams, such as types 4 and 5, drain more quickly, especially in the presence of heat. The distribution piping carries already expanded foam and the discharge device distributes the foam without further expansion. Therefore, the system has sole hydraulic considerations which must be addressed by the installer to ensure delivery of effective foam to the discharge device.

Nozzles should be straight bore, as fog nozzles tend to strip away most of the air in the foam, resulting in poor expansion ratio and a very wet foam quality. To provide a discharge distribution over a large area, rotation nozzles or rotor nozzles are generally used. Alternatively, multi-orifice nozzles have been developed. The foam consists of a homogeneous bubble structure and low proportioning rates, typically from 0.3% to 1.0% with either Class A or B foam concentrates. More information on CAFS can for example be found in [30].

NFPA 11 [31] includes recommendations for the design and installation of foam fire-extinguishing systems, including CAFS. The generation of foam is considered to provide better foam quality than nozzles where foam generation occurs in the nozzle itself. For fire hazards (indoors) in buildings where spill fires may occur, NFPA 11 recommends an application equivalent to 4.1 mm/min with film-forming foams and 6.5 mm/min with protein foams. For CAFS, NFPA 11 recommends a dimensioning according to the system's approval requirements but not lower than 1.63 mm/min for petroleum products. No design and installation recommendations are given for Class A fires in NFPA 11, but CAFS is used for wildland fires (portable equipment) and for example for the protection of waste bunkers in recycling plants and cable tunnels. The foam provides a certain adhesion to vertical surfaces, helping to prevent or delay spread of fire between different objects. With rotating nozzles located at the ceiling, each nozzle can cover a relatively large surface area.

Figure 9 shows a multi-orifice nozzle under operation and the foam quality from a hand-held nozzle.

Figure 9: A multi-orifice CAFS nozzle under operation and the foam quality from a hand-held nozzle demonstrating a certain adhesion to vertical surfaces. Photo: RISE.

There are examples of fixed-pipe CAFS installations in roadway tunnels and even an incident where a fixed system successfully controlled a freight truck fire after manual operation of the system [32].

According to one system manufacturer that was interviewed, a concern with a ceiling mounted CAFS in a ro-ro space is that the vehicles would block the effect of foam application. Only a fire-fighter will be able to extinguish a fire concealed by vehicles. To supplement the fixed system, CAF (Compressed Air Foam) fire-fighting hose lines are proposed which would work for both Class A and B fires. As discussed elsewhere in the report, the shielding effect of vehicles is not unique for a CAFS.

CAFS are usually fire tested with Class B fuel spill fires, for example to UL 162 [33] or FM 5130 [34] standards. After a hydrocarbon pool fire has been extinguished, there is a water spray discharge for 5 minutes. After this water spray application period, re-flash and burn-back tests are conducted to verify the integrity of the foam blanket. What is important here to note is that CAFs can work with sprinklers. Therefore, a system design with both over-head water sprinkler application and CAF is possible, where CAF nozzles integrated in the deck can limit or extinguish a flammable liquid spill fire and over-head sprinklers or water spray nozzles would provide cooling and limit the heat exposure from a shielded fire to adjacent vehicles and the space above.

Asselin [35] lists several benefits with fixed-pipe CAFS as compared to traditional foam-water spray systems:

- **CAF discharge reaches the fire:** The high momentum of CAF distribution, combined with the strength of the foam bubbles, allows the foam to effectively penetrate the fire plume, making fire extinguishment quicker.
- **Produces a uniform foam of very small, strong bubbles:** This results in improvement in foam drainage time, better fuel-vapor barrier and longer burn-back time. This corresponds to extended fire protection after the foam has been discharged.
- **Produces a foam blanket that offers better thermal radiation protection:** The foam blanket stays in place for extended periods of time on top of a fuel and sticks to vertical surfaces, offering good thermal protection for the fuel against fire exposure.
- **Improves visibility during fire conditions:** CAFS significantly reduce steam production during fire extinguishment, ensuring good visibility inside the hazard area.
- **Quantity of water and foam concentrate significantly reduced:** The design density for CAFS represents only 25% of the water requirement for standard foam-water sprinkler systems.
- **Easier clean-up after a fire:** CAFS use significantly less water and foam, requiring less drainage and water treatment after a fire.

Table 13 summarizes the pros and cons of CAFS.

Table 13: Pros and cons for CAFS.

Compressed Air Foam Systems (CAFS)	
Compressed Air Foam (CAF) is generated by injecting compressed air into a foam solution. CAFS is able to deliver a range of useful foam consistencies, labeled from type 1 (very dry) to type 5 (wet), which are controlled by the air-to-solution ratio, and, to a lesser extent, by the foam concentrate-to-water percentage.	
Pros	**Cons**
Increased foam momentum enables it to penetrate flames and reach the fuel surface.	Vehicles may obstruct the distribution of foam from a ceiling mounted system.
Possesses greater stability, with respect to drainage, than air-aspirated foams.	Environmental impact of foam.
Forms a blanket over the fire, blocking radiation, reducing gaseous fuel production, and cooling the fuel.	High maintenance requirements and more failure modes than automatic sprinklers.
Uses much less water and foam concentrate than traditional foam-water systems for flammable fuel spill fires.	Water damage and ship stability issues.
Equally effective with or without enclosing compartment.	Not tested for ro-ro space applications nor recognized in SOLAS.
Provides and effective ignition-retarding barrier.	Manual system operation may be intentionally delayed due to concerns with clean-up of foam.
Visibility in protected area during discharge.	
Effective for both Class A and B fires.	
Easier clean-up after a fire.	

11.2 Foam-water sprinkler and foam-water spray systems

Foam-water sprinkler and foam-water spray systems shall be designed with the recommended discharge density in the installation standards, depending on the design purpose of the system. Foam-water systems differ from conventional foam systems in that when the foam concentrate runs out, water discharge shall continue. The foam concentrates functions as an additive to improve the performance of the system and when there is no more foam concentrate, the system will continue to function with only water. The design density must therefore be high enough to be effective with only water for all fire hazards of the intended application.

Discharge devices may be either air-aspirated or non-air aspirated. Air-aspirated sprinkler devices are relatively large and use a mixing chamber having openings for air. They produce high-quality foam but are rarely used because they are more expensive than non-air aspirated devices. Air-aspirated sprinkler devices are therefore not discussed further here. Non-air aspirated devices are standard water spray nozzles or automatic sprinkler heads that have been tested and approved, for example in accordance with UL 162 or FM 5130. If a high-quality foam has been produced, water striking onto the floor at the end of the foam discharge should not destroy the foam blanket. This is part of the approval testing.

Several types of foam concentrates, recommended by NFPA 16 [36] for the discussed application, are summarized in Table 14.

Table 14: Types of foam concentrates recommended by NFPA 16 for use with foam-water sprinkler and foam-water spray systems.

Type of foam concentrate	Description	Application
Alcohol-resistant foam concentrate (AFFF/ARC)	Contains a polymer that forms a protective layer between the burning surface and foam, preventing foam breakdown by alcohols in the burning fuel.	Fuels containing oxygenates, or fires of liquids based on or containing polar solvents.
Aqueous film forming foam (AFFF) concentrate	Acts as a barrier to exclude air or oxygen and to develop a film on the fuel surface that can suppress fuel vapors from being formed.	Hydrocarbon fuel, alcohol, or water-miscible fuels.
Film forming fluoroprotein foam concentrate (FFFP)	Protects against freezing, corrosion, and bacterial decomposition and resists fuel pickup.	Hydrocarbon fuels.

A foam-water spray system uses open water spray nozzles attached to a piping system. The system is connected to a water supply through a deluge valve and the foam agent is proportioned into the water stream. The deluge valve is opened manually or by the operation of a fire detection system installed in the protected space. When it opens, water flows into the piping system and foam discharges from all nozzles. A deluge system has a time delay between the detection of a fire, or decision to activate the system, and the discharge, due to the time required to operate the valve and filling of the piping network.

A foam-water spray system should be designed for a discharge rate of at least 6.5 mm/min. Water-soluble and certain flammable liquids as well as polar solvents that are destructive to conventional foams require the use of alcohol-resistant foams. Figure 10 and Figure 11 show fire testing in accordance with UL 162 of a foam-water spray system.

Figure 10: Fire testing in accordance with UL 162 of a foam-water spray system. A flammable liquid pool fire was extinguished within a few minutes. Photo: RISE.

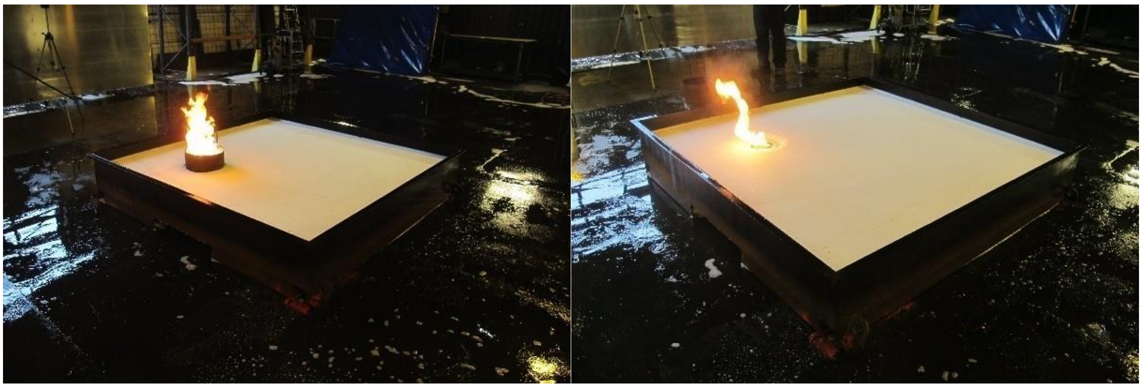

Figure 11: Fire testing in accordance with UL 162 of a foam-water spray system. Burn-back test conducted after the application of water spray on the blanket of foam. When a stovepipe planted vertically in the foam is removed, the foam blanket shall either restrict or flow over and reclose the burning area. Photo: RISE.

A foam-water sprinkler system employs automatic sprinklers connected to a source of foam concentrate and a water supply. The system could be a wet-pipe, dry-pipe, or a pre-action system. For wet-pipe systems, it is worth noting that the piping shall be pre-filled with a mixed solution of foam agent and water. Depending on solutions, they may deteriorate when left in the pipe for extended periods of time and the quality of the pre-mix needs to be regularly checked.

NFPA 16 recommends that sprinklers with a nominal operating temperature between 121°C and 149°C should be used to limit the number of sprinklers that operate in a fire. Automatic foam-water sprinkler systems should be designed for a discharge rate of at least 6.5 mm/min. The minimum operating area for automatic foam-water sprinklers is 465 m². In case the minimum recommended flow rate is used, the foam discharge must last for a minimum of 10 minutes. However, for systems with higher discharge rates, this lower limit can be reduced to 7 minutes. If the supply of foam concentrate has been consumed in full, the system shall discharge water until it is manually terminated.

The primary advantage of foam-water spray and foam-water sprinkler systems over conventional water-based fire extinguishing systems, without the use of a foam agent, is the improved performance on flammable liquid pool fires, i.e. Class B fires. For ro-ro spaces, where flammable liquid spill fires may be directly shielded from the over-head application of water spraying sprinklers or nozzles, foam may offer a significant performance improvement. Use of foam can also boost the systems' capabilities of dealing with fires in solid combustibles, i.e. Class A fires. It is particularly effective at handling fires in polymers, e.g. plastics, which melt, drip, and subsequently form pool fires.

A reduction of the discharge densities stipulated in MSC.1/Circ.1430 to a discharge density of 6.5 mm/min, as per the recommendations in NFPA 16, would need be investigated. It should also be regarded that foam-water spray and foam-water sprinkler systems require a higher level of maintenance to ensure reliable operation and that there are more possible failure modes as compared to an automatic sprinkler system.

Table 15 summarizes the pros and cons of these systems.

Table 15: Pros and cons for foam-sprinkler sprinkler and foam-water spray systems.

Foam-water sprinkler and foam-water spray systems	
A foam additive improves the effectiveness of water for flammable liquid spill fires.	
Pros	**Cons**
Effective for both Class A and B fires.	Difficult to extinguish smaller fires that are hidden, by obstructions, from the direct application of water.
Significantly improved performance in suppressing flammable fuel spill fires as compared to pure water.	Environmental impact of foam.
Radiant heat energy that is absorbed by the fuel is reduced.	Water damage and ship stability issues.
	Not tested for ro-ro space applications.
	Increased system complexity and potentially reduced reliability.
	For automatic foam-water sprinkler systems, tactical operation of the system is not possible.
	Manual system operation of foam-water spray systems may be intentionally delayed due to concerns with clean-up of foam.

11.3 Water curtains

From time to time in the past decades, water curtains have been proposed to be used in ro-ro spaces, with the intent to 'isolate' an area of vehicles under fire from spreading to other parts of the space and to prevent or limit the spread of combustion gases and heat. Fire tests with water curtains were conducted during the tests in Denmark in the early 1960's [25] that likely formed the baseline for the requirements in Resolution A.123(V). These tests did, however, only involve a fuel spill fire that spread along the simulated deck surface.

Water curtains are not recognized in any fire protection standards and there is limited publicly available information from fire tests. The technology could be used to reduce the heat flux from an external fire to an object, for example when protecting outdoor storage tanks with flammable liquids or gases. The water curtain can be directed downwards, in front of the storage tanks to be protected, or the water spray can be directed directly towards the mantle surface of the storage tanks. Buchlin [37] has attempted to investigate the effectiveness of both options. The results show that one or more water curtains can effectively reduce the radiation levels from a fire. The efficiency increases with the number of nozzles in the water curtain and a reduction of between 50% and 75% of the radiant heat can be expected. A typical mass flow rate is 2 kg/s (120 litre/minute) per length meter. If the water spray is instead directed to hit the mantle surface, radiation absorption improves and can be as high as 90%. However, this requires a certain distance between the nozzles and the mantle surface so that the water spray from the individual nozzles overlaps. The typical flow of water is between 0.15 to 0.25 kg/s per square meter (i.e. 9 to 15 liters/minute and square meter).

Water curtains can also be used in buildings instead of walls or doors. Cheung [38] has conducted fire tests to study the design of water curtains in or in front of vertical openings and how much heat radiation reduction that can be achieved. A literature study made before the fire tests showed that the most significant parameters for high radiation reduction are the size of the water drops, its concentration and the width of the water spray. The fire tests were performed in two rooms connected to each other via a vertical opening. Each room had a length of 4.0 m, a width of 2.9 m and a ceiling height of 2.6 m. The fire source was placed in one room. Gas temperatures and radiant heat were measured in the adjacent room. The water curtain in the vertical opening between the two rooms was provided with flat spray nozzles. The parameters studied were different nozzle pressures, the flow rate, fire size and various nozzles. The thermo-elements in the adjacent room showed that the water curtain had a good cooling ability, but the cooling was independent of the nozzle pressure. The study showed that the water curtain does not consist of a continuous layer of water. In the space between the water droplets, hot flue gases can pass. The test results showed that the radiation reduction increased from 36% to 57% when water pressure increased from 4 bar to 6 bar. The relative improvement in radiation reduction increased when the fire size was increased. The nozzle with the smaller nozzle opening (3/8") reduced the heat radiation better than the larger opening nozzle (7/16").

Cong [39] has conducted a series of large-scale fire tests in a tunnel, having a length of 100 m, a width of 12.75 m and a height of 6.7 m with water mist curtains. A fire test source with a heat release rate of 3 MW was used. The results indicate that before water mist curtain activation, the temperature at fire rapidly increased. After the water mist curtain was started, the temperature at the fire source still rose and stabilized, while the temperature on both sides of the water mist curtain decreased, especially on the protected side. Neither the temperatures at the curtain nor the temperature on the protected side exceeded 180ºC. The study also shared some real cases of water mist curtain used for fire partitions. It was concluded that water mist is a valuable option a as fire partition due to highly efficient cooling and radiant heat blocking. Water mist curtains can also limit or prevent smoke spreading to improve conditions during evacuation and manual fire-fighting. The study does also call for more research and that related codes and specifications should be developed.

Water mist sprays can reduce heat transfer by heat radiation from a fire to an object to be protected, thereby delaying or preventing further spread of fire. This is because water in finely divided form effectively absorbs heat radiation from the fire. Försth [40] has conducted a theoretical and experimental study on how this radiation absorption can be optimized. Water is very effective in absorbing heat radiation, but on the other hand, the distance the radiation passes through the droplets itself is relatively short. The parameter studied in the project was the so-called volumetric absorption cross-section, which indicates the heat output [W] absorbed per volume unit of water, [m³] at a given radiation intensity, [W/m²]. Figure 12 shows the result for different water droplet diameters. On the x-axis, the radiation temperature is indicated. This is the temperature of the object that gives rise to heat radiation, typically a sooty flame or a burning surface. The hotter a radiant object is, the shorter the wavelength of the heat radiation. From the Figure 12, it appears that when the temperature increases, the absorption decreases. This is because the water absorbs less heat radiation, the shorter the wavelength is. As the wavelengths become so short that they are in the visible wavelength range, water is transparent, that is, it absorbs very little heat radiation.

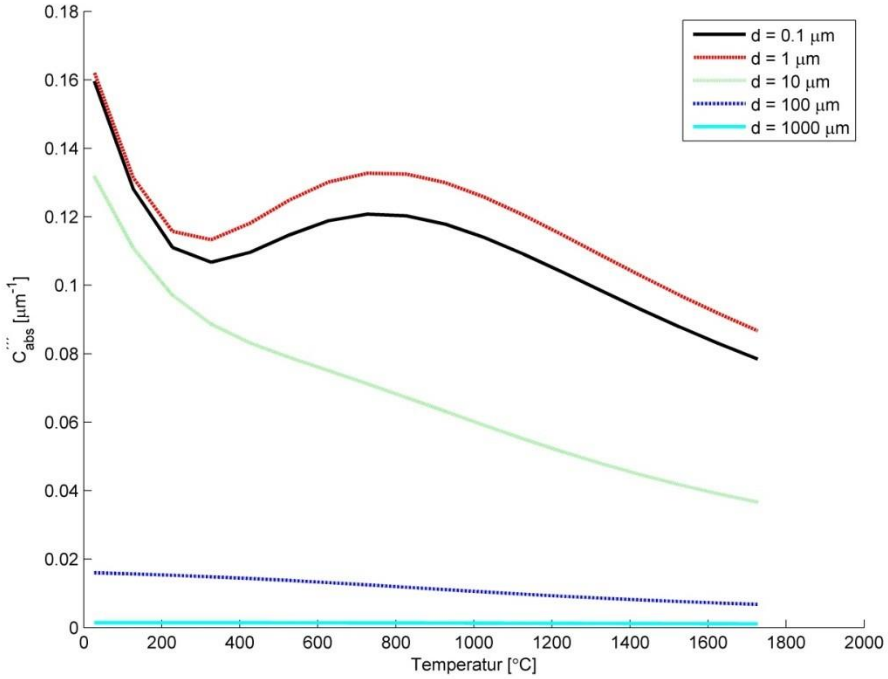

Figure 12: The absorption of heat radiation by water droplets.

The figure also shows that there is an optimum droplet diameter d ≈ 1 μm as these water droplets absorb the radiation most effectively. However, such small water droplets can be difficult to accomplish in practice. In addition, it should be noted that the droplets are vaporized by the heat radiation and that the diameter therefore varies during the lifetime of a droplet. For extremely small drops, absorption is most effective for radiation temperatures around 800°C, which is a typical flame temperature in fires.

Table 16 summarizes the pros and cons of these systems.

Table 16: Pros and cons for water curtains.

Water curtains	
Water is used to form a curtain that prevents the spread of smoke/heat/radiation from a fire and attenuates the heat radiation.	
Pros	**Cons**
Non-toxic and poses no environmental risk.	Limited fire test information available.
Can reduce radiation levels from a fire, thus preventing or delaying fire spread.	Not recognized by available fire protection standards.
	Requires very small water droplets to be effective.
	Vehicles need to be separated in the longitudinal direction with a "firebreak", i.e. a safety distance spacing of cargo and to allow a certain water spray width. This results in deck areas that cannot be used for payable load and in practice, it is likely that the separation distance will be longer than the minimum required distance as vehicles cannot be parked optimal.
	Consumes water which may otherwise be sprayed directly onto the fire.
	Water damage and ship stability issues.
	Water curtains need to be supplemented by any of the other fire-extinguishing systems discussed in the report in order to control, suppress or extinguish a fire.

12 CHALLENGES AND RELEVANT RESEARCH FOR FIXED FIRE-EXTINGUISHING SYSTEMS IN RO-RO SPACES

This chapter discuss challenges "for a ro-ro space fire-extinguishing system as well as two relevant research projects where fire suppression of ordinary combustibles with water spray and water mist nozzles have been studied.

12.1 General challenges for a ro-ro space fire-extinguishing system

The challenges for a fixed fire-extinguishing system to suppress or control a vehicle fire in a ro-ro space can be summarized as follows:

- Ro-ro spaces are very large with a virtually unlimited supply of air (oxygen).
- The fire load is very high, with tightly packed vehicles.
- Short minimum free vertical distance (clearance) from the top of high vehicles to the underside of the stiffeners of the deck, in the order of 400 mm to 500 mm. This may reduce the possibilities for a uniform distribution of water or foam-water from over-head sprinklers or nozzles.
- The “umbrella effect”, i.e. that the fire may shielded from direct application of water from over-head sprinklers or nozzles.
- Limited possibilities for pre-wetting as the body of a vehicle is designed to withstand environmental conditions as rain and snow.
- Potential for fast fire spread to other decks as there may be no fire rating of the deck above.
- Difficult to undertake manual fire-fighting due to limited accessibility on the deck along with reduced visibility by smoke, toxic gases, potential for unexpected fuel spill fires, explosion hazards, jet-flame fires, etc.
- Ship stability issues with high water flow rates or long discharge duration times.

Figure 13 illustrates some of the issues listed above.

Figure 13: Freight trailers on a ro-ro deck, illustrating the short distance between the vehicles and the limited deck height. Photo: RISE.

12.2 Specific challenges for automatic sprinklers or nozzles

For automatic sprinklers or nozzles (i.e. sprinklers or nozzles that are activated by the heat from a fire), it is essential that the vertical distance from the underside of the deck to the thermal element is within certain limits to provide as fast activation as possible. For unobstructed ceiling constructions, the general recommendation in for example NFPA 13 [41] is that the distance between the sprinkler deflector and the ceiling shall be a minimum of 25 mm and a maximum of 305 mm.

Sprinklers or nozzles at the underside of 'obstructed ceiling constructions' need to be positioned such that the ceiling construction in terms of beams, trusses, or other members do not affect the water distribution. On the other hand, a vertical distance too far from the deckhead will influence the activation time. Figure 14 illustrates an automatic sprinkler or nozzle installed at a certain vertical distance below the underside of the deckhead as to avoid obstruction to discharge but ensuring activation of the thermal element.

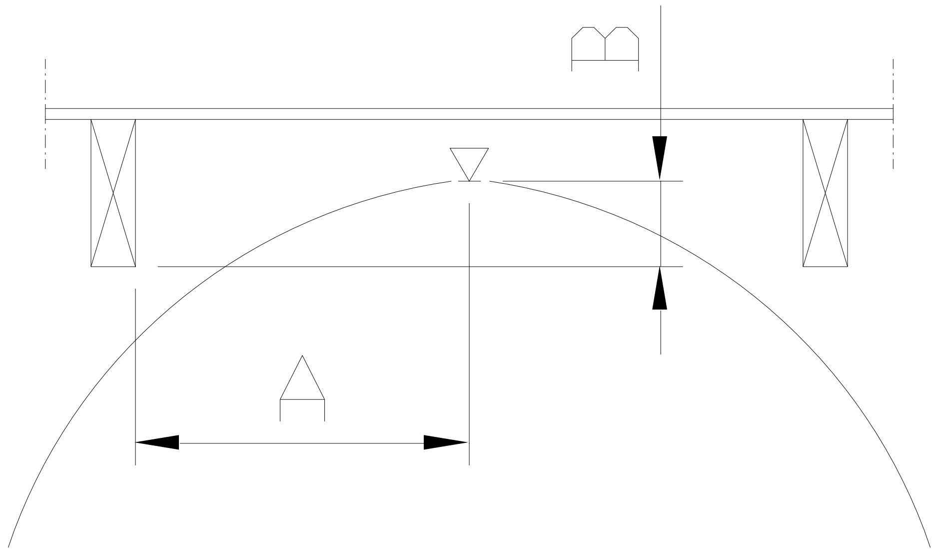

Figure 14: Positioning of an automatic sprinkler or nozzle to avoid obstruction to discharge but ensuring activation of the thermal element.

NFPA 13 provides recommendations of the minimum and maximum allowed vertical distances for obstructed ceiling constructions as follows:

1) Sprinklers should be installed with the deflectors within the horizontal planes of 25 mm to 152 mm below structural member and a maximum distance of 559 mm below the ceiling deck.
2) Sprinklers should be installed with the deflectors at or above the bottom of the structural members to a maximum of 559 mm below the ceiling deck.
3) Sprinklers should be installed in each bay of obstructed constructions, with the deflector located a minimum of 25 mm and a maximum of 305 mm below the ceiling deck.
4) Where sprinklers are listed for use under other ceiling constructions features or for different distances, they shall be permitted to be installed in accordance with their listing.

Sprinklers could be positioned in each bay formed by the beams which would allow that they are positioned closer to the deckhead, to improve the activation time. However, the water spray will therefore be obstructed such that overlap of water sprays from adjacent sprinklers on opposite sides of the beams is prevented. NFPA 13 states that sprinklers installed under obstructed ceiling constructions need to be positioned such that the development of the water spray is not obstructed by the beams that support the ceiling. This requires that the sprinklers are installed with their deflectors at a certain distance below the underside of the deckhead.

In MSC.1/Circ.1430, this problem is recognized and paragraph 4.5 states that: "Sprinklers or nozzles should be positioned at or within 0.6m of the underside of the deck, in order to distribute water over and between all vehicles or cargo in the area being protected". However, new ro-ro passenger ships are becoming larger and in recent new-built ships, the height of the deck girders can reach up to about 1.5 m. In a submission [42] to the Sub-committee on Ship Systems and Equipment (SSE), CESA raises two concerns. Firstly, that the web height of which is an obstacle which will make it difficult to obtain an undisturbed water spray from sprinklers or nozzles installed close to the deck. In addition, the deck girders typically have a T-shape, both the girders' web and flange/face plate that constitute a larger shadow area for a sprinkler or nozzle fitted at or within 0.6 m from the underside of the deck. The second concern is related to the fire test procedures in MSC.1/Circ.1430 and the fact that these do not reflect the actual ceiling construction conditions.

The SSE Sub-committee prepared draft amendments to MSC.1/Circ.1430 in the document SSE 5/WP.4 [43], taking into account submitted documents. Paragraph 4.5 was revised as follows:

"4.5 Sprinklers or nozzles should be positioned in such a way that:

.1 they are not exposed to damage by cargo;

.2 undisturbed spray is ensured; and

.3 water is distributed over and between all vehicles or cargo in the area being protected.

Automatic sprinklers or nozzles should be positioned and located so to provide satisfactory performance with respect to both activation time and water distribution."

Although the revised text does not provide any detailed guidelines on how to re-solve the problem, it highlights the importance that the activation of automatic sprinklers or nozzles could be severely influenced by the celling construction.

Ceilings with beams also need special consideration when designing a fire detection system as the 'pockets' formed between the beams can trap smoke. Fire codes such as the NFPA 72 [44] that covers the application, installation, testing, and maintenance of fire alarm systems recognize this problem and recommends smoke detectors in every pocket.

12.3 Relevant research on fire suppression of solid combustible fires

Some research with high relevance for fire-extinguishing systems in ro-ro spaces is elaborated below.

12.3.1 *Research by RISE in the IMPRO-project*

Within the IMPRO-project, intermediate-scale fire suppression tests were conducted using a freight truck trailer mock-up with authentic geometry [12]. The tests were designed to vary the following parameters; the system technology, i.e. a traditional water spray system or high-pressure water mist system, the water discharge density, the water pressure (water spray system only) maintaining the water discharge density, thereby varying the droplet size and the momentum of the water spray and finally the exposure of the fire, i.e. the use of a roof on the trailer mock-up.

The mock-up was constructed from square iron rods and the bottom and the roof of the platform of the mock-up was constructed from steel plates. Six rows of commodity were positioned on the platform such that longitudinal and transversal gaps of 100 mm were created between the stacks of commodity. For the tests with the roof of the trailer mock-up the number of commodity pallets was reduced to two rows, i.e. one third of the amount of commodity used for the tests without the roof. Figure 15 shows the test set-ups.

Figure 15: An illustration of the arrangement of the commodity on the trailer mock-up, showing the steel sheet screen on the right-hand long side. A similar screen was positioned on the left-hand side. The photo to the right shows the trailer mock-up with the roof installed. Note that less amount of commodity, two times two pallet loads instead of two times six pallet loads was used for test without the roof [12].

A steel sheet (nominally 0.8 mm thick) screen was positioned parallel with the long sides of the trailer mock-up. The screens had a height (2.8 m) that corresponded to the height of the 'cargo space' of the mock-up. The tops of the screens were levelled with the top level of the roof over the trailer mock-up, i.e. 4.0 m above floor level. The length of 2.7 m was shorter than the overall length of the mock-up but covered the two central stacks of commodity and extended halfway along the length (on either side) of the adjacent stacks. The surface temperatures of the steel screens were measured at 18 different measurement points.

A standardized commodity, the EUR Std Plastic commodity, was used as the fire load. It consists of empty Polystyrene (PP) cups without lids, placed upside down (i.e. open end down), in compartmented cartons, 120 cups per carton. The cartons measures 600 mm × 400 mm × 500 mm (L × W × H) and are made from single-wall, corrugated cardboard [45]. Each wood pallet in the tests contained a total of eight commodity cartons.

Table 17 summarizes the water spray and high-pressure water mist nozzles used in the tests, their K-factor, nominal water discharge density, system operating pressure and estimated media droplet size.

Table 17: The water spray and high-pressure water mist nozzles used in the tests, their K-factor, nominal water discharge density, system operating pressure and estimated media droplet size [12].

System	Nominal discharge density [mm/min]	Nozzle K-factor [metric]	Minimum orifice diameter [mm]	System operating pressure [bar]	Water flow rate per nozzle [litre/min]	Estimated median droplet size [µm]
Water spray	5	43.2	8.3	1.2	48	889
Water spray	10	80.6	11.1	1.4	96	1028
Water spray	10	43.2	8.3	4.9	96	559
Water spray	15	103.7	12.7	1.9	144	1014
Water mist	3.75	3.6	-	100	36	~150
Water mist	4.6	4.4	-	100	45	~150
Water mist	5.8	6.1	-	84	56	~150

For both types of systems, piping system consisted of four branch lines with nozzle connections for eight nozzles at a 3.2 m × 3.0 m nozzle spacing, i.e. a coverage area of 9.6 m² per nozzle. The vertical distance measured from the nozzles to the roof (when used) of the trailer mock-up was 0.5 m and the vertical distance to the top of the stacks of commodity approximately 1.0 m.

The tests were conducted under an Industrial Calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire in order to measure the heat release rate. The fire suppression system was manually activated at a convective heat release rate of 3 MW, which equaled a total heat release rate of approximately 5 MW.

Figure 16 shows the heat release rate histories for the exposed as well as the shielded fire scenario.

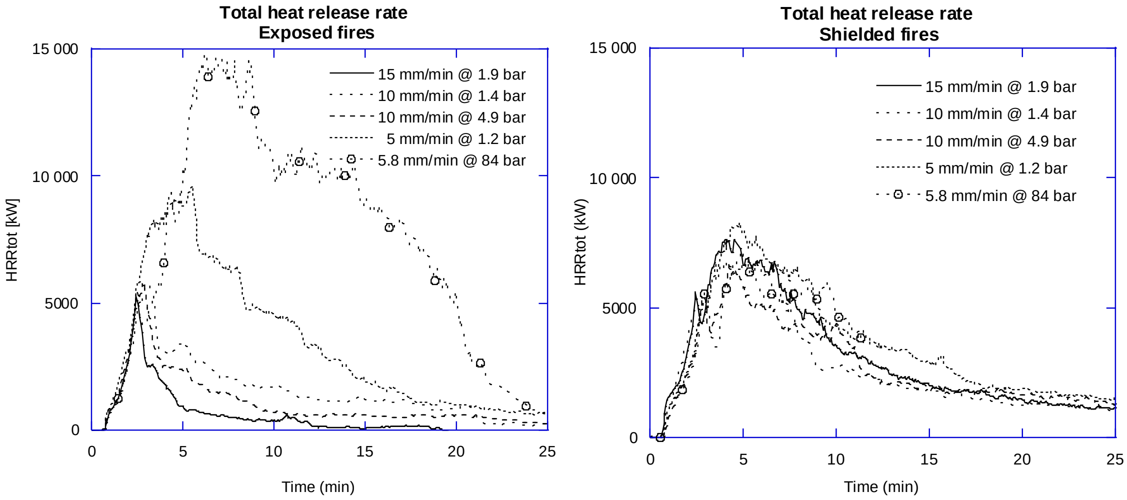

Figure 16: The total heat release rate histories for the exposed (left) and the shielded fires (right) in the simulated freight truck trailer [12].

The tests where the fires were fully exposed to the water spray shows that there is a clear relationship between the level of performance and the water application rate. A discharge density of 15 mm/min provided immediate fire suppression, 10 mm/min fire suppression, and 5 mm/min fire control. The high-pressure water mist system provided fire control at a discharge density of 5.8 mm/min. However, the tests at 3.75 and 4.6 mm/min, respectively, went out of control and are therefore not illustrated in the graphs as the tests were manually terminated.

For the final test (not shown in the heat release rate graphs), the activation of the water spray system (10 mm/min at 4.9 bar) was intentionally delayed until the fire size was twice as large as in the other tests. Despite this, the fire was almost immediately suppressed.

Based on the heat release rate measurements, the total and convective energy generated during the duration of the tests can be calculated. Figure 17 shows this data. For the fires where the fire was shielded from direct water application, the tested systems had a limited effect on the total heat release rate and the associated total energy, as almost all combustible material was consumed. The most efficient reduction of the convective heat release rate and the associated convective energy of the water spray systems was demonstrated with 10 mm/min at the higher system operating pressure of 4.9 bar.

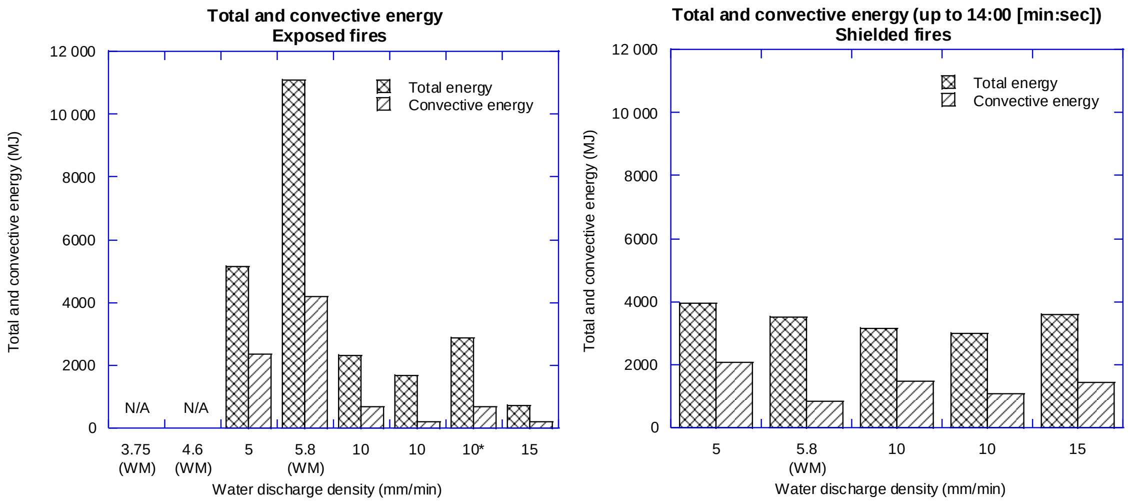

Figure 17: The total and convective energy for the exposed (left) and the shielded fire (right) scenarios. The water mist tests at 3.75 mm/min and 4.6 mm/min, respectively, went out of control, were manually terminated and are therefore not illustrated in the graphs. The terminology "WM" denotes Water Mist and the "*" indicates the test with delayed activation of the system [12].

The high-pressure water mist system reduced the total convective energy to a level that was less than all water spray system tests which underlines the improved cooling efficiency of the smaller water droplets.

The surface temperatures of the steel sheet plates positioned along both long sides of the trailer mock-up were measured at eighteen (18) different measurement points, on each of the steel sheet plates. Three of the measurement points were positioned on the horizontal top surface of the steel plate and the remaining fifteen measurement points on the vertical surface facing the trailer mock-up. Figure 18 shows the mean temperature for the exposed as well as the shielded fire scenario.

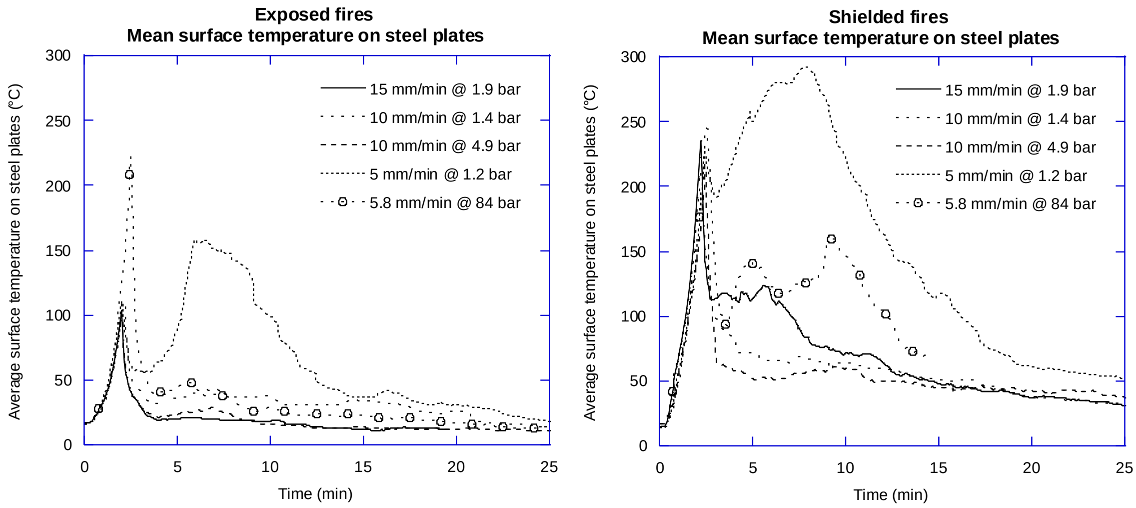

Figure 18: The mean temperature of the steel sheet plates for the exposed (left) and the shielded fire (right) scenarios [12].

For the exposed fire scenario, the reduction of the mean steel sheet temperatures correlates reasonably well with the suppression ability of the tested systems. However, the high-pressure water mist system reduced the temperatures better than it provided fire suppression. For the shielded fires, a higher discharge density generally reduced the mean steel sheet temperature better, although the reduction was better at the 10 mm/min density as compared to the 15 mm/min density. The high-pressure water mist system, discharging 5.8 mm/min reduced the mean temperature better than did the water spray system with a discharge rate of 5 mm/min.

12.3.2 *Research by FM Global comparing sprinklers and water mist*

Yu [46] has investigated factors affecting the efficiency of water mist suppression of solid combustible fires in an open environment. The objective of the project was to identify the key factors for suppressing solid combustible fires in open environment and expand the database for water mist suppression of solid combustible fires.

Cooling of the fire environment, air inerting and displacement as well as radiation attenuation are factors that are often associated with suppression of fire in enclosures when using water mist. For the suppression of ordinary, solid combustibles in an open environment, the water flux on fuel surfaces is an essential factor. This factor is depending on the application density, the fire plume penetration capability of the water droplets and the tendency of droplet deposition on fuel surfaces in a gas stream.

To investigate this, fire suppression tests were conducted with two tests commodities that are commonly used for fire testing of automatic sprinkler systems, the Class II commodity and the Cartoned Expanded Plastic (CEP) commodity. The Class II commodity consists of a metal liner inside a large cardboard box with six layers of corrugated cardboard and the CEP commodity of expanded Polystyrene plastics meat trays inside single-layer cardboard cartons. The latter is considered the most severe of these commodities.

The commodity was arranged either in a rack (the Class II commodity) that was four pallet loads long, two pallet loads wide and two pallet loads high or placed directly on the floor (the CEP commodity) one pallet load only high. The overall storage height of the Class II commodity was 2.77 m and the height of the CEP commodity arrangement was 1.22 m. The vertical distance from the top of the commodity to the open sprinklers or water mist nozzles was almost identical for both commodity arrangements, 1.65 m and 1.68 m, respectively. Figure 19 shows the fire test set-ups for each of the commodities.

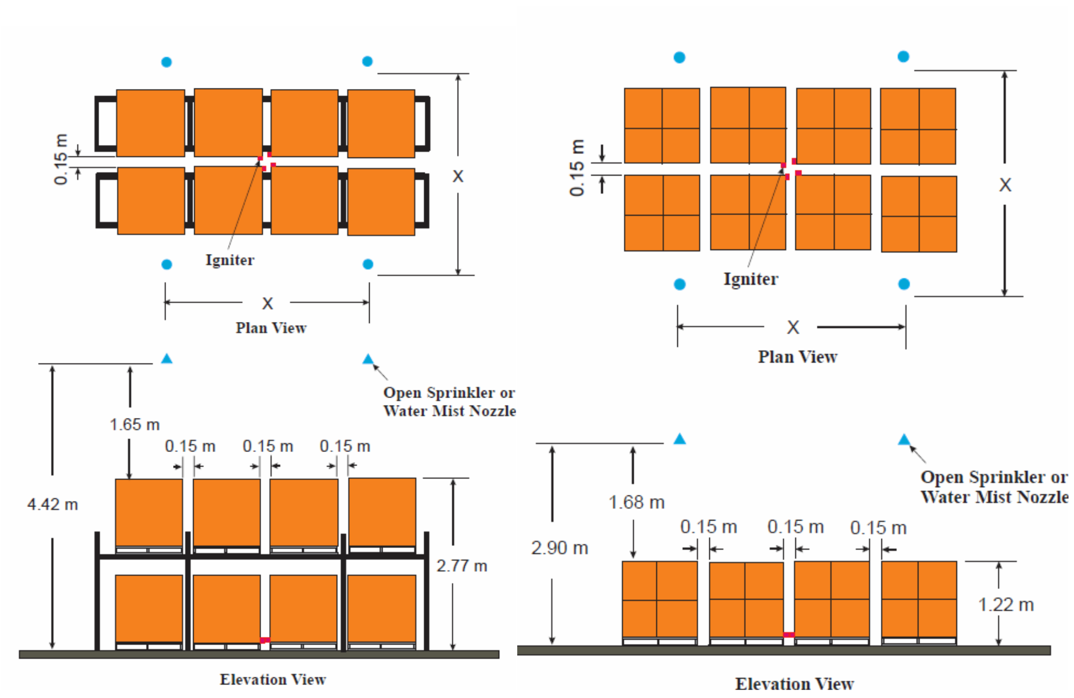

Figure 19: The fire test set-up with the Class II commodity (left) and the CEP commodity (right) [46].

Three different water mist nozzles and one K80 sprinkler were tested at different operating pressures. Table 18 shows the sprinkler and water mist nozzle operating and test conditions.

Table 18: The sprinkler and water mist nozzle operating and test conditions for the tests conducted by FM Global [46].

Sprinkler or water mist nozzle	Operating pressure (bar)	Downward spray thrust force per nozzle (newton)	Spray angle (degrees)	Nozzle spacing (m x m)	Median droplet diameter (µm)	Application density (mm/min)
Sprinkler	0.5	6.9	115	3 × 3	1400	6.1
	0.9	12.4			1200	8.1
Water mist A	100	71.0	110	2.6 × 2.6	75	6.1
Water mist B	16.5	40.0	110	3 × 3	218	8.1
Water mist C	20	18.3	110	3 × 3	345	4.1
	44.8	41.0	110		265	6.1
	79.3	72.5	110		220	8.1

The operating pressure of the sprinkler was either 0.5 bar or 0.9 bar and the operating pressures of the water mist nozzles ranged from 16.5 bar to 79.3 bar. The operating pressures and nozzle spacings were selected such that the application density was 6.1 mm/min or 8.1 mm/min, respectively. The lower application density of 6.1 mm/min was used for the Class II commodity tests and the higher application density of 8.1 mm/min was used for the CEP commodity tests. An additional test was conducted using 4.1 mm/min for the Class II commodity.

The commodity array was ignited at the base of the central vertical flue and water application from the array of four sprinklers or nozzles was started when the convective heat release rate reached 1000 kW. The heat release rate was measured with a large-scale calorimeter during the tests. Table 19 summarizes the fire tests results.

Table 19: Fire test summary for the Class II and CEP commodity tests conducted by FM Global [46].

Commodity	Sprinkler or water mist nozzle	Application density (mm/min)	Median droplet diameter (µm)	Combined spray thrust force in the fire plume (N)	Plume uplift force at sprinkler/nozzle elevation at water application time (N)	Fire spread to the ends of fuel array?
Class II	Sprinkler	6.1	1400	3.2	15.1	Spread to one end. Fire marginally suppressed.
Class II	Water mist nozzle A	6.1	75	52.9	14.6	Spread to both ends. Fire not suppressed.
Class II	Water mist nozzle C	6.1	265	21.5	16.9	No. Fire suppressed.
Class II	Water mist nozzle C	4.1	345	9.6	13.6	Spread to both ends. Fire not suppressed.
CEP	Sprinkler	8.1	1200	6.7	16.7	No. Fire suppressed.
CEP	Water mist nozzle C	8.1	220	38.0	13.2	Spread to one end. Fire marginally suppressed.
CEP	Water mist nozzle B	8.1	218	21.0	15.1	No. Fire suppressed.

Figure 20 shows the heat release rate histories for the tests.

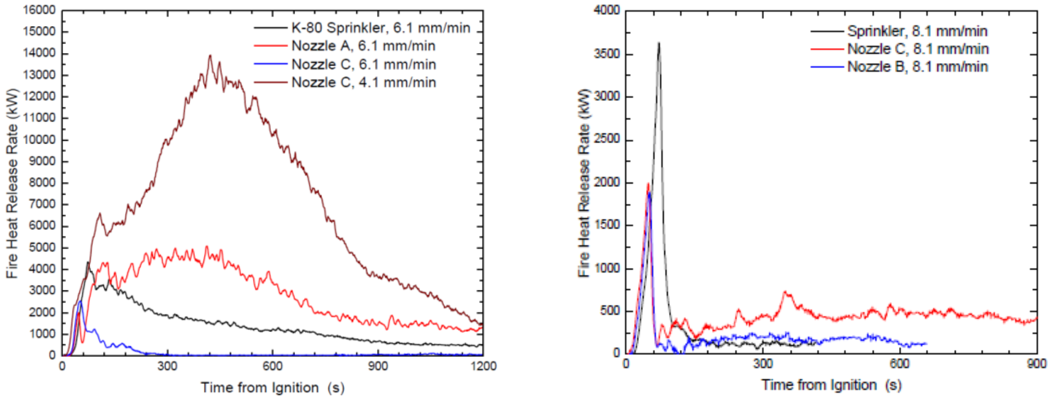

Figure 20: The heat release rate histories for the tests with the Class II commodity (left) and the CEP commodity (right) conducted by FM Global [46].

The following was concluded from the tests:

- Fire suppression was affected by the application density and spray characteristics such as droplet size, discharge velocity and spray thrust force, not by nozzle configuration and operating pressure.
- Fire suppression in open environment could not be achieved if the median droplet diameter of the water sprays was not sufficiently large for the fire challenge.
- Fire suppression in open environment with water mist required water densities comparable to those of the sprinklers.
- The downward spray thrust force was not a critical factor for fire suppression. However, when the spray exceedingly overpowered the fire plume, the highly disturbed flames tended to increase fire spread and thus worsened the suppression result.

12.3.3 *Research by FM Global testing water mist nozzles for HC-2 and HC-3 occupancies*

Yu [47] have conducted additional fire tests using deluge and automatic water mist nozzle systems. The objective of the tests was to determine the ceiling height limits for water mist fire suppression for two occupancy hazard categories denoted HC-2 and HC-3 according to FM Global.

All fire tests were conducted using a low-pressure water mist system, where the operating pressure was 16.5 bar, the discharge rate per nozzle 76 litre/minute and the nozzle spacing 3.05 m by 3.05 m. This corresponded to a discharge density of 8.1 mm/min. The nozzles provided a volume median droplet diameter of 218 µm and the nozzle spray angle was 110°. The nozzles were operated individually by a solenoid valve and were not fitted with a thermal element. However, the thermal sensors for initiating the discharge had Fast Response characteristics and a nominal operating temperature of 74°C.

The fire tests with automatic operation of the nozzles could have some validity for ro-ro spaces and are discussed here. Fire tests were also conducted with a deluge operation, however, these tests simulated ceiling heights that are not valid for ro-ro spaces and are therefore not summarised.

According to FM Global, HC-3 occupancies can be described as “Heavily loaded areas with or without plastics”, for example “Manufacturing and nonmanufacturing facilities with higher concentrations of combustibles or shielding of combustibles where the fire hazard could approach the equivalent of nominal 5 ft (1.5 m) high in-process storage of cartoned unexpanded plastic commodities”. Among the examples of such occupancies are:

- Car-sized vehicle repair garages and assembly operations where vehicles are repaired, tested, or assembled with relatively small amounts of fuel in tanks.
- Highway trailers, trucks, boxcars, some mobile homes or similar metal vehicles with combustible interiors with the potential for shielded fire.

A wet-pipe system with traditional automatic sprinklers in HC-3 occupancies with a ceiling height up to 9 m should be designed for 12 mm/min over a design area of 230 m^2. A dry-pipe system should be designed for 12 mm/min over a design area of 330 m^2.

Several fire tests were conducted with fuel arrays representing Hazard Category HC-2 and HC-3 occupancies. The ceiling height was 6.1 m. All dependent on the position of the fire ignition source in relation to the nozzles at the ceiling, between 3 and 13 nozzles activated. Based on these test results, it was concluded that HC-2 and HC-3 occupancies can be protected with automatic low-pressure water mist nozzles for ceiling heights up to 6.1 m, with a water demand of 20 nozzle operations for a safety factor of 50%. This design, i.e. 8.1 mm/min over a design area of 186 m^2 is slightly less demanding compared to the automatic sprinkler system design discussed above. However, it should be noted that the ceiling height is less, only 6.1 m as compared to 9 m.

13 PERFORMANCE CAPABILITY EVALUATION

The performance of the respective new alternative fire-extinguishing systems identified above is discussed under the relevant sections below. In order to have references for comparison, systems recognized in SOLAS are first elaborated.

13.1 Fire-extinguishing systems recognized in SOLAS

The performance of fire-extinguishing systems recognized in SOLAS is elaborated below.

13.1.1 *Water spray systems in accordance with Resolution A.123(V)*

Although this type of system is no longer installed on new ships, it has relevance as long as it is permitted to be used on existing ships. Such system was used in the large-scale fire tests as a reference.

13.1.2 *Automatic sprinkler or deluge water spray systems as per MSC.1/Circ.1430*

Automatic sprinkler or deluge water spray systems designed in accordance with MSC.1/Circ.1430 represent significant performance improvement as compared to systems accordance with Resolution A.123(V). Such system was therefore also used in the large-scale fire tests as a reference.

13.1.3 *Automatic water mist nozzle or deluge systems in accordance with MSC.1/Circ.1430*

As discussed in the report, the expected performance of water mist systems is in principle similar to systems in accordance with Resolution A.123(V). However, the required automatic operation of the system could be very beneficial in an actual fire.

13.1.4 *High-expansion foam systems*

High-expansion foam systems have several benefits that are interesting for ro-ro space applications and they are recognized for use in vehicle spaces and ro-ro spaces (except special category spaces due to concerns with evacuation) that can be sealed from a location outside of the cargo spaces. An effective fill-up of foam in the entire protected space would be an effective means of controlling a fire, especially as foam with the right properties spread across a fuel surface and around obstacles. Foam will limit the exposure from heat radiation from a fire to objects that are not involved. It is essential that high-expansion foam systems are operated very quickly after the onset of a fire, so quick detection and activation systems need to be provided.

The water demand is low as the water content in high-expansion foam is low. However, for large ro-ro spaces the total required water flow rate could be high. For a ro-ro space having a length of 200 m, a width of 30 m and a height of 5 m the total gross volume of the space equals 30 000 m^3. With a submergence time of 5 minutes (in principle in accordance with NFPA 11), a foam expansion ratio of 700, a compensation factor for normal foam shrinkage of 1.15 and a compensation factor for leakage of 1.0 (i.e. no leakage envisioned), the total required water flow rate is almost 10 000 litre/minute. Another drawback is that ducts need to be arranged to supply the fresh air from the outside to generate the foam. For the example given above, more than 7 000 m^3/minute of air would be required. High-level venting need to be provided for air (including combustion gases) that is displaced by the foam.

The FSS Code requires that outside-air foam systems shall have a sufficient foam-generating capacity to completely fill the largest protected space within 10 minutes. This is twice as long as the recommendations in NFPA 11, which is a notable difference.

Inside-air foam systems do not use fresh air for the generation of foam and air is directly supplied from the protected compartment. This requires foam concentrates which are resistant to combustion gases and high temperatures. The main differences compared to conventional high-expansion foam systems are that the foam is generated without the use of a fan, no air need to be supplied and ventilated from the protected compartment and the system is easier and more flexible to install. The generation of foam is, however, negatively affected if the fire is under-ventilated and pyrolysis products are formed, even if the temperature at the generators is rather low. The generation of foam does also decrease considerably when the air temperature is high. Therefore, the size of the protected compartment and the degree of ventilation must be considered when designing a high-expansion foam system using inside air. It is also essential that the system is activated early and that the application rate is sufficiently high.

It should also be regarded that high-expansion foam systems require a high level of maintenance to ensure reliable operation and have more possible modes of failure than automatic sprinkler systems.

13.1.5 *Gas fire-extinguishing systems*

Gas fire-extinguishing systems represent the only type where extinguishment of a fire is the performance objective. Gas systems require a high integrity of the protected volume to be effective as well as ventilation openings or dampers to handle the over-pressure in the space.

Currently, the FSS Code recognizes Carbon Dioxide systems for the protection of ro-ro spaces, however, these systems are not permitted to be used in special category spaces. With an early manual activation (automatic activation is not permitted) and sufficient integrity of the protected space it is likely that these systems are effective.

13.2 Relevant alternative fire-extinguishing systems

The performance of the identified relevant alternative fire-extinguishing systems is elaborated below.

13.2.1 *CAFS*

The Compressed Air Foam Systems (CAFS) represent a technology that has proven very effective on flammable liquid spill fires and solid combustible fires. However, this literature study has not identified any large-scale tests involving vehicles or similar fire hazards.

NFPA 11 has recommendations for the design and installation foam-water spray systems, including compressed air foam systems. The generation of foam is considered to provide better foam quality than nozzles where foam generation occurs in the nozzle itself. For fire hazards (indoors) in buildings where spill fires may occur, NFPA 11 recommends an application equivalent to 4.1 mm/min with film-forming foams and 6.5 mm/min with protein foams. For CAFS, NFPA 11 recommends a dimensioning according to the system's approval requirements but not lower than 1.63 mm/min for petroleum products. The foam provides a certain adhesion to vertical surfaces, thus helping to prevent or delay spread of fire between different objects. However, this density would likely need to be considerably higher for ro-ro space protection than the density sufficient for flammable liquid spill fires.

13.2.2 *Foam-water sprinkler or water spray system*

The primary advantage of foam-water spray and foam-water sprinkler systems over conventional water-based fire extinguishing systems, without the use of a foam agent, is the improved performance on flammable liquid pool fires, i.e. Class B fires. For ro-ro spaces, where flammable liquid spill fires may be directly shielded from the over-head application of water spraying sprinklers or nozzles, foam may offer a significant performance improvement. Use of foam can also boost the systems' capabilities of dealing with fires in solid combustibles, i.e. Class A fires. It is particularly effective at handling fires in polymers, e.g. plastics, which melt, drip, and subsequently form pool fires.

A reduction of the discharge densities stipulated in MSC.1/Circ.1430 to a discharge density of 6.5 mm/min, as per the recommendations in NFPA 16, would need to be investigated.

13.2.3 *Water curtains*

Water curtains have been proposed to be used in ro-ro spaces, mainly with the intent to 'isolate' vehicles on fire from spreading to other parts of the space and to prevent or limit the spread of combustion gases. Specific test data for ro-ro space or similar applications is not available. Large-scale fire tests conducted in a tunnel having a length, width and height (100 m (L) by 12.75 m (W) by 6.7 m (H)) resembling a ro-ro space indicate that the gas temperatures on the “protected” sides of the water mist curtains were reduced. However, the fire size was small (3 MW) compared to the fire size that could be expected on a ro-ro deck.

Research indicates that the optimum water droplet for radiation absorption is approximately 1 μm, and such small water droplets can be difficult to achieve in practice. Test data from fire tests (probably involving water sprays with considerably larger water droplets) protecting outdoor storage tanks with flammable liquids or gases indicate that effective water curtains need to be designed for 120 liters/minute per length meter. A ro-ro space having a width of 30 m would require two water curtains flowing a total of 2 × 30 m × 120 liters/minute = 7 200 litre/min. This flow rate is significantly higher than that required for several of the system designs in MSC.1/Circ.1430. Without spraying water towards the actual fire, it is also likely that the fire would grow out of control. Therefore, if used on a ro-ro space, water curtains need to be supplemented by any of the other fire-extinguishing systems discussed in the report in order to control, suppress or extinguish a fire.

13.3 Theoretical performance capability summary

Table 20 summarizes the performance capabilities of the fire-extinguishing systems discussed in the report. The performance is expressed using three different performance objectives:

- Fire control.
- Fire suppression.
- Fire extinguishment.

The performance is assessed for a flammable liquid fuel spill fire as well as for a fire involving solid combustibles. However, for an actual fire in a ro-ro space, these two types of fires would typically not be isolated but rather combined. Another implication for the evaluation would be the degree of shielding of the fire. As an example, a fire in a fuel spill on the deck surface could be considerably shielded by the bodies of the vehicles. A fire inside the cargo compartment of a freight truck trailer, inside an engine compartment of a vehicle or in the tire of a vehicle would also be more or less shielded. This shielding effect is not part of the evaluation as the degree of shielding could be very different from case to case. For this evaluation, it is therefore assumed that the fires are exposed to the agent being used. However, two of the fire-extinguishing systems discussed in the report are judged to be more effective than the others for a shielded fire; high expansion foam systems gas fire-extinguishing systems.

Table 20: Expected performance capabilities of the fire-extinguishing systems discussed in the report.

System	System type		Fuel spill fire	Solid combustible fire	Comments
Fire-extinguishing systems recognized in SOLAS					
Manually activated water spray system in accordance with Resolution A.123(V)	Deluge		Fire control	Fire control	Considered out of date for modern fire hazards on ro-ro spaces
Automatic sprinkler or deluge water spray system in accordance with MSC.1/Circ.1430	Wet-, dry- or pre-action		Fire control	Fire suppression	Per definition an automatic activation, which is advantageous
	Deluge		Fire control	Fire suppression	Improved performance compared to a water spray system in accordance with IMO Resolution A.123(V)
Automatic water mist nozzle or deluge systems in accordance with MSC.1/Circ.1430	Wet-, dry- or pre-action		Fire control	Fire control	Tested and approved with a fire test procedure that does not reflect modern fire hazards on ro-ro spaces
	Deluge		Fire control	Fire control	
High expansion foam systems in accordance with the FSS code.	Total flooding, outside/inside air foam	Submergence 5 minutes (NFPA 11)	Fire extinguish-ment	Fire suppression	Early operation important
		Submergence 10 minutes (FSS Code)	Fire extinguish-ment	Fire suppression	Early operation very important
Gas fire-extinguishing system	Total flooding		Fire extinguish-ment	Fire extinguishment	Compartment integrity is important
Relevant alternative fire-extinguishing systems					
Compressed air foam system (CAFS) per NFPA 11	Deluge		Fire extinguish-ment	Fire control (uncertain)	Limited relevant test data available for solid combustible fires
Foam-water sprinkler or water spray systems per NFPA 16	Wet/dry/pre-action		Fire extinguish-ment	Fire control	Per definition an automatic activation, which is advantageous
	Deluge		Fire extinguish-ment	Fire control	-
Water curtains, i.e. two on each side of the fire	Deluge		-	-	No relevant test data available

Based on the limitations of water curtains described above (13.2.3), and in particular that such system was not judged suitable to replace the currently required water-spraying deluge system in ro-ro spaces, this system was not further considered in the study except for an estimation of the installation cost and the yearly cost associated with the loss of cargo space. The CAFS and the foam-water spray system were selected for further performance capability evaluation thought large-scale fire tests, described below.

13.4 Extinguishing performance based on large-scale fire tests

As the 3rd step of the project, the systems expected to have the best performance in combination with a feasible cost was tested in large-scale fire tests. Two alternative, commercially available fixed fire-extinguishing systems were selected; a foam-water spray system and a CAF system. The fire suppression performance of the two systems was compared to the performance of a deluge water spray system designed in accordance with Resolution A.123(V) and MSC.1/Circ.1430, respectively. The former is commonly used on existing ships, the latter is used on ships constructed after 2012.

The fire scenario used in the tests simulates a partly shielded (to the water spray) and partly exposed fire in a freight truck trailer. All dimensions of the test set-up except for the overall length are realistic and the system nozzles were installed to simulate an actual fire suppression installation in terms of nozzle height, nozzle clearance and nozzle spacing. The test set-up resembles the one used in the IMPRO-project, however, the combustible loading was less. The heat release rate of the fire was measured, and the steel sheet screens instrumented with thermocouples simulated adjacent vehicles to where the fire could potentially “spread”.

It can be concluded that the deluge water spray system designed in accordance with MSC.1/Circ.1430, that discharged 10 mm/min of plain water had a superior performance. The fire size was controlled, and the fire control capabilities and direct cooling of the steel sheet screens would likely have prevented fire spread to adjacent vehicles. The discharge density of 5 mm/min associated with the system designed in accordance with Resolution A.123(V) limited the fire, but not to a level where fire spread to a space above or to adjacent vehicles definitely can be judged to be prevented.

The performance of the foam-water spray system was more or less between the two water spray systems, which is in line with the discharge density of 6.5 mm/min. There were limited signs of performance improvements due to the use of the foam additive, however for a potential fire scenario that also is involving a spill fire, improvements of using foam are likely to be achieved.

Two tests were conducted with the CAF system. One test with an unaltered fire test set-up and one test where the fire scenario was fully exposed, less amount of combustibles was used and with an earlier system activation. Both fire tests were terminated as limited fire suppression was observed. Part of the reason for the system performance is probably that the discharge density of 2.4 mm/min is significantly less compared to the other systems. It is, however, worth noting that the particular CAF systems used in the tests is approved for flammable liquid fuel fires and that normally the extinguishing mechanism is creating a physical barrier to suppress vapours and reduce the amount of oxygen. For the type of fire present for this test series more work would be needed to find a recipe that would create more of a cooling effect while keeping the advantages of the CAF bubbles. CAF distribution can also be modified to apply the CAF in the areas that are more critical. The advantage of CAF is that it can be adjusted and modified to suit the different needs since it is created at the system and the recipe can be changed and tailored for different applications.

The large-scale fire tests are described in detail in Annex A2 of the report.

14 EVALUATION OF WATER CONSUMPTION

The water consumption of the water-based fire-extinguishing systems discussed in the report is briefly discussed under the relevant sections of the report. Given in this chapter is a summary of these discussions applied for a particular space. The starting point for the estimation is based on the following measures of a fictive ro-ro space:

- Length: 200 m.
- Width: 30 m.
- Height: 5 m.

This corresponds to a ro-ro space area of 6 000 m^2 and a volume of 30 000 m^3.

For the hydraulic design purposes of a system with automatic sprinklers or nozzles, the design area is where it is assumed that all sprinklers or nozzles will operate simultaneously. For many systems, the hydraulically most remote area and design area are the same. The hydraulically most remote area is that portion of the system where components, materials and system size is the hydraulically most challenging to deliver water to at the required water discharge density.

For the relevant deluge systems, it was assumed that the minimum required two sections operate simultaneously. In this case, the corresponding area is 2 sections × 20 m (L) × 30 m (W) = 1 200 m^2.

Table 21 shows the result of the estimation. In this case, the minimum theoretical water flow rates were calculated. However, as a rule of thumb, the actual flow rate is typically approximately 20% higher than the minimum theoretical flow rate, due to hydraulic imbalances in the system pipe-work.

When reading the table, it is important to consider that the performance ability of the systems is significantly different (as per the discussion in Section 13) and a direct comparison of the water flow rates should be made with care.

Table 21: The minimum, theoretical total flow water flow rates for the water-based fire-extinguishing systems discussed in the report.

System	System type		Minimum discharge rate [mm/min]	Minimum operating area [m²] or submergence volume [m3]	Total water flow rate [litre/min]	Relative consumption
Fire-extinguishing systems recognized in SOLAS						
Manually activated water spray system in accordance with Resolution A.123(V)	Deluge		5	1 200 m²	6 000	100%
Automatic sprinkler or deluge water spray system in accordance with MSC.1/Circ.1430	Deluge		10	1 200 m²	12 000	200%
	Wet		15	280 m²	4 200	70%
	Dry/pre-action			365 m²	5 475	91%
Automatic nozzle or deluge water mist systems* in accordance with MSC.1/Circ.1430	Deluge, low pressure		4.6	1 200 m²	5 520	92%
	Deluge, high pressure		2		2 400	40%
	Water mist, high pressure	Wet	1.9	280 m²	532	9%
		Dry/pre-action		365 m²	694	12%
	Water mist high pressure	Wet	2.6	280 m²	728	12%
		Dry/pre-action		365 m²	949	16%
High expansion foam systems** in accordance with the FSS code.	Total flooding, outside /inside air foam	Submergence 5 minutes (NFPA 11)	1.64	6000 m², 30 000 m³	9 900	165%
		Submergence 10 minutes (FSS Code)	0.82		4 900	82%
Relevant alternative fire-extinguishing systems						
Compressed air foam system (CAFS) per NFPA 11	Deluge		1.63 (NFPA 11)	1 200 m²	1 956	33%
Foam-water sprinkler or water spray systems per NFPA 16	Deluge		6.5 (NFPA 16)	1 200 m²	7 800	130%
	Wet/dry/pre-action			480 m²	3 120	52%
Water curtains, i.e. two on each side of the fire	Deluge		120 litre/minute per length meter	2 × 30 m	7 200	120%***

* Exemplified with currently approved low- and high-pressure water mist systems.

** Exemplified with the minimum submergence time of 10 minutes given in the FSS Code and a more relevant submergence time of 5 minutes given in NFPA 11.

*** As discussed, water curtains need to be supplemented by any of the other fire-extinguishing systems discussed in the report in order to control, suppress or extinguish a fire. If this system is a water-based system, the total flow water flow rate is higher.

15 EVALUATION OF INSTALLATION COSTS

To perform an estimation of the installation cost as accurate as possible, the calculations were based on the RoPax reference ship presented in Figure 21. It is expected that the equipment and material costs would be the same for new-built and existing ships. However, the installation costs would probably be slightly less on a new-built ship as the overall lay-out of the system, the required spaces for equipment, the routes for the piping, the positions of nozzles, etc. can be resolved during the engineering phase of a project.

Figure 21: Picture of the RoPax reference ship. Photo: Stena Rederi.

To make this result generally applicable to the world fleet of ro-ro passenger ships, scalability according to the deck size is discussed. Maintenance costs in the maritime context could not be retrieved.

Deck 4 of the RoPax reference ship is an open ro-ro space (Figure 22). This deck is enclosed by the deckhead and side shell bulkheads and mainly naturally ventilated through large openings in the ship sides and through the open aft. The space is largely exposed to the ambient environment; temperature, wind, humidity, etc. and the installation of an automatic (i.e. thermally activated nozzles) system would not be permitted. However, for the cost estimation presented here, this fact is overlooked for the foam-water sprinkler system. The same fact was overlooked for the system using water curtains.

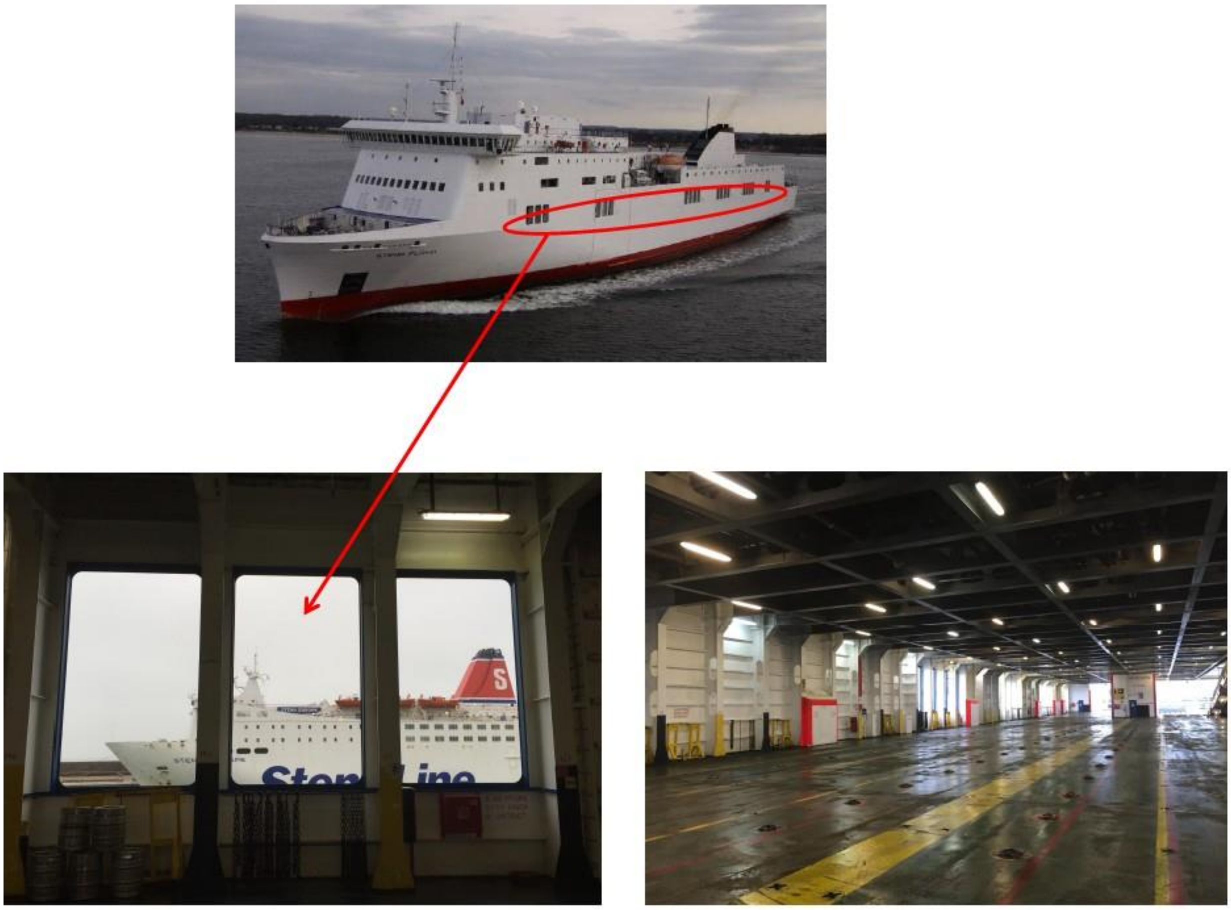

Figure 22: View of Deck 4 of the RoPax reference ship. Photos: Stena Rederi.

15.1 Selected fire-extinguishing systems

Based on the discussion in Section 11, a cost estimation was performed for the four following systems:

- CAFS, i.e. a system employing open nozzles connected to a foam generator unit connected to a water supply.
- A foam-water sprinkler system, i.e. a system employing automatic sprinklers connected to a source of foam concentrate and to a water supply designed in accordance with the recommendations in NFPA 16.
- A foam-water spray system i.e. a system employing open nozzles connected to a source of foam concentrate and to a water supply designed in accordance with the recommendations in NFPA 16.
- Water curtains, despite the conclusion in the project that they have limited effectiveness as a stand-alone system.

Specific installation requirements for these systems are discussed later in this section.

It was assumed that all equipment and material as water pumps, foam proportioning equipment, the tank for the foam concentrate, control valves, pipe-work and discharge nozzles would be installed.

The costs for the following equipment and material were excluded in the system cost estimate as it was assumed to exist onboard the ship:

- Both the main and emergency sources of power.
- The sea water connection.
- The fire detection system. It was supposed that a fire detection system was available and that the fire detection sections correspond with the deluge systems of the foam-water spray and CAF system, respectively.

Three system suppliers were contacted to conduct the cost estimation, however, only two of these responded. The cost estimation was conducted in close dialogue with these two companies and the costs for certain more expensive equipment as the water pumps was verified with additional companies.

15.2 Basic requirements

The basic requirements detailed in Table 22 were assumed to be fulfilled, based on the requirements in MSC.1/Circ.1430 and MSC.1/Circ.1271. Note that the wording of the requirements may be slightly altered compared to the original text.

Table 22: Basic requirements on the systems as based on MSC.1/Circ.1430 and MSC.1/Circ.1271.

Paragraph	Requirement	Comment
3.2	All systems hall be divided into sections. Each section shall be capable of being isolated with one section control valve. The section control valves should be located outside the protected space, be readily accessible without entering the protected space and their locations should be clearly and permanently indicated. It should be possible to manually open and close the section control valves either directly on the valve or via a control system routed outside the protected space.	From MSC.1/Circ.1430 and relevant for all three systems in the study. It should be noted that all systems in the cost estimation have the same number and size of the sections.
3.2.3	System piping, components and pipe fittings in contact with the foam concentrate should be compatible with the foam concentrate and be constructed of corrosion resistant materials such as stainless steel, or equivalent. Other system piping and foam generators should be galvanized steel or equivalent.	From MSC.1/Circ.1271 and relevant for all three systems in the study.
3.2.4	Means for testing the operation of the system and assuring the required pressure and flow should be provided by pressure gauges at both inlets (water and foam liquid supply) and at the outlet of the foam proportioner. A test valve should be installed on the distribution piping downstream of the foam proportioner, along with orifices which reflect the calculated pressure drop of the system. All sections of piping should be provided with connections for flushing, draining and purging with air.	From MSC.1/Circ.1271 and relevant for all three systems in the study.
3.2.5	The quantity of foam concentrate available should be sufficient to produce a volume of foam equal to at least five times the volume of the largest protected space at the nominal expansion ratio, but in any case, not less than enough for 30 min of full operation for the largest protected space.	From MSC.1/Circ.1271. Note that specific requirements for each of the systems in the study are given later in the document.
3.8	The system shall have two redundant water pump units.	MSC.1/Circ.1271 does, however, not require that the foam proportioning equipment and tank for the foam concentrate should be redundant, and this approach is adopted in this cost estimate.
3.9	The system should be fitted with a permanent sea inlet and be capable of continuous operation using sea water.	This require that any foam agent is compatible with sea water.
3.10	Distribution piping should be constructed from galvanized steel, stainless steel or equivalent.	From MSC.1/Circ.1271 and relevant for all three systems in the study.
3.11	A means for testing the automatic operation of the system and, in addition assuring the required pressure and flow rate should be provided.	From MSC.1/Circ.1430. The first requirement is simply the inspectors' test valve, the second requirement will require a permanently installed water flow meter and pressure gauge at the water supply.
3.19	Any foam concentrate used as system additives should comply with the Revised Guidelines for the performance and testing	From MSC.1/Circ.1430. For this cost estimate, this requirement can be over-looked, but it is essential

	criteria and survey foam concentrates for fixed fire-extinguishing systems (MSC.1/Circ.1312).	that the foam does not contain PFOA and PFOS or is completely fluorine-free. The foam agent needs to be compatible with sea water.
3.23	All release controls for deluge systems…of all sections valves should be available and grouped together in a continuously manned control station or the safety centre, if provided.	From MSC.1/Circ.1430. All deluge valves are located on Deck 1 on the RoPax reference ship.
3.11	The length of a deluge section (along the lanes) should not be less than 20 m but not exceed 48 m.	From MSC.1/Circ.1430. Some of the deluge sections on the RoPax reference ship exceed the maximum deluge section length.
4.2	Deluge systems should be designed for the operation of the two adjacent deluge sections having the greatest hydraulic demand at the minimum design density.	From MSC.1/Circ.1430. For this cost estimation, see instruction below.
4.4	Automatic sprinklers or nozzles should have a temperature rating of between 121°C and 149°C and standard response characteristics.	From MSC.1/Circ.1430. This is required to reduce the number of activated sprinklers. Relevant to the foam-water sprinkler system only.
4.5	The maximum horizontal spacing between sprinklers or nozzles is 3.2 m.	From MSC.1/Circ.1430. This is required for both automatic and open sprinklers or nozzles. For this cost estimation, see the discussion below.

15.3 Number of sections and number of nozzles

Table 23 shows the sections, sections lengths and number of nozzles for the current water spray system (‘drencher’) installation on the RoPax reference ship. This information was used for the cost estimation, irrespective of the system type.

Table 23: The sections, sections lengths and number of nozzles on the RoPax reference ship. Note: Partly, the same section numbering is used, despite that the sections are on different decks.

Deck	Section	Section length (m)	No. of nozzles per section
1 – lower hold	N.8	20.8	29
	N.9	20.8	24
	N.10	20.0	24
	N.11 (under ramp)	33.1	14
	N.12	20.0	19
	Total section length:	**114.7**	**110 nozzles in 5 sections**
2 – car deck	N.8	20.0	15
	N.9	20.4	18
	N.10	20.8	29
	N.11 (above ramp)	24.8	14
	N.12	20.0	21
	Total section length:	**220.7**	**97 nozzles in 5 sections**
3 – main deck	N.1	30.4	38
	N.2	28.0	33
	N.3	20.0	48
	N.4	20.8	48
	N.5	20.8	48

	N.6	20.8	44
	N.7	23.2	36
	Total section length:	**164.0**	**295 nozzles in 7 sections**
4 – open deck	N.13	50.0	50
	N.14	31.2	42
	N.15	20.8	48
	N.16	20.8	48
	N.17	20.8	48
	N.18	21.1	41
	N.19	31.3	27
	N.20 (under ramp)	30.1	9
	Total section length:	**196.0**	**313 nozzles in 8 sections**
			In total 815 nozzles in 25 sections

15.4 Pipe network

Drawings of the specific pipe-work on the RoPax reference ship was not available. Therefore, an estimation of the total length of piping was made, refer to Table 234. Given that the number of sections and nozzles are equal for all systems (as per the discussion below) except for the system utilizing water curtains, a similar system design using a tree pipe-work configuration is applicable. The pipe lengths for all three systems are thereby equal, although the hydraulic design would result in different pipe dimensions as reflected in the cost estimations.

Table 24: The estimated pipe lengths on the RoPax reference ship.

Deck	Section	Section length (m)	Pipe length for distribution pipe-work (m)	Pipe length for branch lines (m)
1 – lower hold	N.8	20.8	30	140
	N.9	20.8	50	140
	N.10	20.0	70	130
	N.11 (under ramp)	33.1	70	70
	N.12	20.0	90	100
			310 meters	**580 meters**
2 – car deck	N.8	20.0	60	140
	N.9	20.4	80	140
	N.10	20.8	140	140
	N.11 (above ramp)	24.8	170	70
	N.12	20.0	190	100
			640 meters	**590 meters**
3 – main deck	N.1	30.4	110	200
	N.2	28.0	70	190
	N.3	20.0	70	140
	N.4	20.8	90	140

	N.5	20.8	110	140
	N.6	20.8	130	140
	N.7	23.2	150	160
			730 meters	**1110 meter**
4 – open deck	N.13	50.0	90	170
	N.14	31.2	70	100
	N.15	20.8	100	140
	N.16	20.8	120	140
	N.17	20.8	140	140
	N.18	21.1	160	140
	N.19	31.3	90	110
	N.20 (under hoistable ramp)	30.1	90	110
			860 meters	**1030 meter**
Total (rounded off)			**2 500 meters**	**3 300 meters**

15.5 Specific requirements for the systems

Specific technical requirements for each of the identified relevant alternative fire-extinguishing systems are further detailed below.

15.5.1 *CAFS*

The system should be of the deluge type with the number of sections and number of nozzles as described in Table 23. The system should be designed for the simultaneous operation of the two adjacent deluge sections having the greatest hydraulic demand. For the estimation of the total water flow rate, it is presumed that sections N.17 and N.18 are used. The total number of nozzles of these sections is 48 plus 41 = 89 nozzles.

The minimum design density (water) shall be set to 2.5 mm/min. It should be emphasized that this figure is arbitrary and not based on any scientific research or any testing. It is presumed that the coverage area per nozzle is 10 m^2 and the water flow rate is 25 litre/minute per nozzle. The design density and design area correspond to a minimum theoretical water flow rate of approximately 2 225 litre/min. The actual flow rate is typically approximately 10% higher than the minimum theoretical flow rate, due to hydraulic imbalances in the system pipe-work and each of the two water redundant water pumps should have a capacity of approximately 2 450 litre/min each.

The foam supply shall be sufficient for a duration time of 60 minutes. At a 1% foam concentration, the required foam concentrate storage tank shall be at least 1 470 litres. The possibility for continuous supply of sea water after this period is required.

Note: MSC.1/Circ.1271 for high-expansion foam systems requires that the quantity of foam concentrate should be sufficient to produce a volume of foam equal to at least five times the volume of the largest protected space at the nominal expansion ratio, but not less than enough for 30 minutes of full operation for the largest protected space. For CAFS, it was judged that a longer duration time is needed compared to a high-expansion foam system as the foam does not fill up the volume as would a high-expansion foam system.

A Class B foam that does not contain PFOA and PFOS or is completely fluorine-free shall be assumed to be used. The foam agent needs to be compatible with sea water as it was assumed that the potable water supply on the on the RoPax reference ship is not sufficiently large.

15.5.2 *Foam-water sprinkler system*

The system should be of the dry-pipe type with the number of sections and number of nozzles as described in Table 23 i.e. the number of sections is identical with the other two system alternatives.

The system design area should be 465 m^2 as per NFPA 16.

The minimum design density (water) shall be set to 6.5 mm/min as per NFPA 16. It is presumed that the coverage area per nozzle is 10 m^2 and the water flow rate is 65 litre/minute per nozzle. The design density and design area correspond to a minimum theoretical water flow rate of approximately 3 022 litre/min. The actual flow rate is typically approximately 20% higher than the minimum theoretical flow rate, due to hydraulic imbalances in the system pipe-work and each of the two water redundant pumps should have a capacity of approximately 3 600 litre/min.

Upright, standard-coverage sprinklers with a nominal operating temperature between 121°C and 149°C should be used as per NFPA 16 and MSC.1/Circ.1430 and Standard Response characteristics as per MSC.1/Circ.1430.

The foam supply shall be enough for a duration time of 10 minutes as per NFPA 16. At a 3% foam concentration, the required foam concentrate storage tank shall be at least 1 200 litres. The possibility of continuous supply of sea water after this period is required.

A fluorine-free Class B foam shall be assumed to be used. The foam agent needs to be compatible with sea water as it was assumed that the potable water supply on the on the RoPax reference ship is not sufficiently large.

15.5.3 *Foam-water spray system*

The system should be of the deluge type with the number of sections and number of nozzles as described in Table 23.

The system should be designed for the simultaneous operation of the two adjacent deluge sections having the greatest hydraulic demand. For the estimation of the total water flow rate it is presumed that sections N.17 and N.18 are used. The total number of nozzles of these sections is 48 plus 41 = 89 nozzles.

The minimum design density (water) shall be set to 6.5 mm/min as per NFPA 16. It is presumed that the coverage area per nozzle is 10 m^2 and the water flow is 65 litre/minute per nozzle. The design density and number of nozzles in the design area correspond to a minimum theoretical water flow rate of 5 785 litre/min. The actual flow rate is typically approximately 20% higher than the minimum theoretical flow rate, due to hydraulic imbalances in the system pipe-work and each of the two water redundant pumps should have a capacity of approximately 7 000 litre/min each.

The foam supply shall be enough for a duration time of 10 minutes. At a 3% foam concentration, the required foam concentrate storage tank shall be at least 2 200 litres. The possibility of continuous supply of sea water after this period is required.

A Class B foam that does not contain PFOA and PFOS or is completely fluorine-free shall be assumed to be used. The foam agent needs to be compatible with sea water as it was assumed that the potable water supply on the on the RoPax reference ship is not sufficiently large.

15.5.4 *Water curtains*

The system should be of the deluge type with a horizontal distance between curtains of approximately 40 m, which corresponds to the approximate length of two freight trucks with trailer. The system should be designed for the simultaneous operation of the two adjacent curtains having the greatest hydraulic demand.

The minimum design flow rate shall be 120 litre/minute per length meter. The internal width of the ship is approximately 20 m, which would correspond to a total required flow rate of 2 × 20 m × 120 litres/minute = 4 800 litre/min. The actual flow rate is typically approximately 20% higher than the minimum theoretical flow rate, due to hydraulic imbalances in the system pipe-work and each of the two water redundant pumps should have a capacity of approximately 5 800 litre/min each.

It is assumed that vehicles need to be separated 3 m in the longitudinal direction with a “firebreak”, i.e. a spacing of cargo to provide a safety distance and to allow a certain water spray width in-between cargo. However, this figure is arbitrary and not based on any scientific research or any testing. Nevertheless, it results in deck areas that cannot be used for payable load and in practice, it is likely that the separation distance will be longer than the minimum required distance as vehicles cannot be parked optimal.

Given the assumptions discussed above, Table 25 shows the number of deluge valves that is required and the number of ro-ro space areas that are separated by the water curtains on each deck.

Table 25: The number of deluge valves and the areas that are separated by the water curtains on each deck.

Deck	Valve number	Number of areas on each deck
1 – lower hold	1:1	2
2 – car deck	2:1	2
3 – main deck	3:1	4
	3:2	
	3:3	
4 – open deck	4:1	4
	4:2	
	4:3	
	In total 8 sections	**In total 12 areas**

15.6 Issues where additional input from the supplier was desired

Additional input was required for the following issues from the suppliers of the systems:

- **Drainage of water.** This issue is specifically related to CAFS that produce a high-quality foam with long drainage times. Could the slow drainage of water in the foam result in ship stability problems? The issue was discussed with the CAFS supplier and it was concluded that this is probably not a problem. Water will drain out of the foam (although at a low rate) and the water can be drained from a deck via the scuppers. Additionally, water will evaporate from the foam due to the heat from a fire.
- **The possibility for continuous application of sea water after the end of foam application.** This issue is specifically related to CAFS. The issue was discussed with the CAFS supplier and it was concluded that the discharge of water would continue after the supply of foam has ended, if there is electrical power supply for the water pumps available.
- **The total water flow rate.** This issue was resolved during the process and the figures are given in the cost estimation conditions discussed in the report.
- **The type of foam agent and the design concentration.** This issue was also resolved during the process and the type of foam agent and the concentration are given in the cost estimation conditions discussed in the report.

The approximate footprint and weight of the following equipment was requested for all three systems:

- Water pumps.
- Foam-proportioning equipment.
- Foam agent tank.
- Air compressor equipment.

The power demand for the following equipment was requested for all three systems.

- Water pumps.
- Air compressor equipment.
- For the CAF system, the power demand of the complete foam generating unit was given.

15.7 General cost estimation assumptions

To facilitate the cost estimation, the following assumptions were made due to the similarities of all three (except for the system using water curtains that is less complex) systems:

- The type of piping, including couplings and hangers was assumed to similar for the systems, i.e. galvanized pipes with pressure rating PN16 and the estimated cost was only a function of the estimated pipe sizes. The pipe sizes for the foam-water spray system and CAFS was assumed to be similar. Reduced pipe sizes were assumed for the water spray system and the system using water curtains as the water flow rates are less.
- The cost for the sprinklers and nozzles for the foam-water sprinkler system, foam-water spray system and for the system using water curtains was assumed to be similar.
- The cost for the interface between the foam-water spray system and CAFS and the fire detection system onboard the ship was assumed to be similar.
- The cost for data and supply cables was assumed to be similar for all systems, but lower for the system using water curtains as this system is slightly less complex.
- The estimated man hours for the engineering, documentation, commissioning and any training was assumed to be similar for the foam-water sprinkler system, foam-water spray system and CAFS, but less for the system using water curtains as this system is slightly less complex. The same estimated cost per working hour was used.
- The estimated man hours for the installation was assumed to be similar for the foam-water sprinkler system, foam-water spray system and CAFS, but less for the system using water curtains as this system is slightly less complex. The same estimated cost per working hour was used. The cost for travels and allowance was not included.

15.8 Cost estimations

The cost estimations are specified below for each of the identified relevant alternative fire-extinguishing systems.

15.8.1 *CAFS cost estimation*

The cost for the CAFS was based on the use of two complete and redundant CAFS system foam generating units. Each unit contains a water pump, a foam inductor and an air compressor. However, the units were connected to a common 1 500-litre foam concentrate storage tank large enough for a discharge duration of at least 60 minutes. The capacity of the foam generator unit was about 2 500 litre/min (water and foam pre-mix flow rate) plus the required volume flow rate of compressed air.

The cost for the pipe-work assumed that DN125 and less galvanized distribution piping and DN40 and less galvanized branch lines were used.

A fully biodegradable, fluorine-free Class B foam agent was used in the cost estimation. The system can provide a continuous application of sea water after the end of foam application. Table 26 shows the estimated cost for an installation on the RoPax reference ship.

Table 26: The estimated installation cost for the CAFS on the RoPax reference ship.

	Quantity or man hours	**Cost per quantity or man hour (Euro)**	**Total cost (Euro)**
CAFS units	2	€ 145 500	€ 291 000
Foam agent tank in plastic composite	1	€ 2 500	€ 2 500
Foam agent, fluorine-free Class B	1 500	€ 5	€ 7 500
Deluge valves, including actuators and control valves	25	€ 500	€ 12 500
Control panels (activation centrals)	2	€ 22 500	€ 45 000
External output modules incl. interconnection cables and junction boxes	28	€ 500	€ 14 000
Data and supply cables	2 500	€ 15	€ 37 500
Pipe-work (distribution pipes) with couplings and pipe hangers	2 500	€ 25	€ 62 500
Pipe-work (branch lines) with couplings and pipe hangers	3 300	€ 15	€ 49 500
Air pipes, pilot air including connectors and hoses	1 500	€ 8	€ 12 000
Interaction with ships fire detection system	1	€ 2 500	€ 2 500
Drainage valves and any other system valves	50	€ 15	€ 750
Open rotary nozzles	815	€ 45	€ 36 675
Engineering, documentation, commissioning and any training	600	€ 100	€ 60 000
Total cost for equipment, material and engineering			**€ 633 925**
Labour cost for the installation work (estimated excluding travels, allowance, etc.)	3 500	€ 80	**€ 280 000**
Overall cost			**€ 913 925**

Table 27 shows the footprint, weight and power demand for the equipment associated with the CAFS installation.

Table 27: The footprint, weight and power demand associated with the CAFS installation.

Type of equipment	**Number of items**	**Dimensions [m], each item**	**Weight [kg], each item**	**Power demand [kW]**
CAFS units	2	Length: 1.75 m Width: 1.50 m Height: 1.37 m	1 280 kg = in total 2 560 kg.	Water pump: 130 kW Air compressor: 55 kW Foam pump (control gear): 8 kW In total: 193 kW
Foam agent tank, cylindrical tank with nominal capacity 1 500 litre in PE	1	Diameter: 1.0 m Height: 2.0 m	Approx. 1 700 kg including the agent	None

15.8.2 *Foam-water sprinkler system cost estimation*

The cost for the pipe-work assumed that DN100 and less sized galvanized distribution piping and DN40 and less galvanized branch lines were used. The cost for the pump unit includes associated equipment such as the electric motor, the support frame, the control panel, valves, a flow meter, etc. Table 28 shows the estimated cost for an installation on the RoPax reference ship.

Table 28: The estimated installation cost for the foam-water sprinkler system on the RoPax reference ship.

	Quantity or man hours	Cost per quantity or man hour (Euro)	Total cost (Euro)
Water pump units, 3 600 litre/min @ 10 bar	2	€ 30 000	€ 60 000
Bladder tank, 1 200 litres, including valves, etc.	1	€ 20 000	€ 20 000
Foam-proportioning equipment	1	€ 2 500	€ 2 500
Foam agent, 1200 litre	1 200	€ 5	€ 6 000
Dry-pipe valves, 4" (DN 100) including main control shut-off valves and all associated equipment	25	€ 2 500	€ 62 500
Air compressor	1	€ 10 000	€ 10 000
Data and supply cables	2 500	€ 15	€ 37 500
Control panels	2	€ 2 500	€ 5 000
Pipe-work (distribution pipes) with couplings and pipe hangers	2 500	€ 20	€ 50 000
Pipe-work (branch lines) with couplings and pipe hangers	3 300	€ 10	€ 33 000
Drainage valves and any other system valves	100	€ 15	€ 1 500
Automatic sprinklers	815	€ 10	€ 8 150
Engineering, documentation, commissioning and any training	600	€ 100	€ 60 000
Total cost for equipment, material and engineering			**€ 356 150**
Labour cost for the installation work (estimated excluding travels, allowance, etc.)	3 500	€ 80	**€ 280 000**
Overall cost			**€ 636 150**

The footprint, weight and power demand of the equipment associated with the water supply, the storage of the foam agent and the foam proportioning equipment is given in Table 29.

Table 29: The footprint, weight and power demand of the equipment associated with the water supply, etc. for the foam-water sprinkler system.

Type of equipment	Number of items	Dimensions [m], each item	Weight [kg], each item	Power demand [kW]
Water pump units, 2 600 litre/min @ 10 bar each	2	Not provided.	Not provided.	110 kW per pump unit
Air compressor	1	Length: 1.00 m Width: 0.50 m Height: 0.80 m	50 kg	2 kW
Bladder tank	1	Length: 2.50 m Width: 1.00 m Height: 1.80 m	760 kg + foam agent = approx. 2 000 kg	None
Foam-proportioning equipment (connected to the tank above)	1	Width: 62 mm Height: 239 mm	13 kg	None
Dry-pipe valves, including shut-off valves (Note: Space requirement estimation rather than actual size)	25	Length: 1.00 m Width: 1.00 m Height: 2.00 m	Approx.: 100 kg = approx. 2 500 kg	None

15.8.3 *Foam-water spray system cost estimation*

The cost for the pipe-work assumed that DN150 and less sized galvanized distribution piping and DN50 and less galvanized branch lines were used. The cost for the pump unit includes associated equipment such as the electric motor, the support frame, the control panel, valves, a flow meter, etc. Table 30 shows the estimated cost for an installation on the RoPax reference ship.

Table 30: The estimated installation cost for the foam-water spray system on the RoPax reference ship.

	Quantity or man hours	Cost per quantity or man hour (Euro)	Total cost (Euro)
Water pump units, 7 000 litre/min @ 10 bar	2	€ 50 000	€ 100 000
Bladder tank, 2 200 litres, including valves, etc.	1	€ 22 500	€ 22 500
Foam-proportioning equipment	1	€ 3 000	€ 3 000
Foam agent, 2 200 litres	2 200	€ 5	€ 11 000
Deluge valves, 6” (DN 150) including main control shut-off valves and all associated equipment	25	€ 2 500	€ 62 500
Data and supply cables	2 500	€ 15	€ 37 500
Control panels	2	€ 2 500	€ 5 000
Interaction with ships fire detection system	1	€ 2 500	€ 2 500
Pipe-work (distribution pipes) with couplings and pipe hangers	2 500	€ 25	€ 62 500
Pipe-work (branch lines) with couplings and pipe hangers	3 300	€ 15	€ 49 500
Drainage valves and any other system valves	50	€ 15	€ 750
Open nozzles	815	€ 10	€ 8 150
Engineering, documentation, commissioning and any training	600	€ 100	€ 60 000
Labour cost for the installation work (estimated excluding travels, allowance, etc.)			**€ 424 900**
Installation cost	3 500	€ 80	**€ 280 000**
Overall cost			**€ 704 900**

The footprint, weight and power demand of the equipment associated with the water supply, the storage of the foam agent and the foam proportioning equipment is given in Table 31.

Table 31: The footprint, weight and power demand of the equipment associated with the water supply, etc. for the foam-water spray system.

Type of equipment	Number of items	Dimensions [m], each item	Weight [kg], each item	Power demand [kW]
Water pump units, 7 000 litre/min @ 10 bar each	2	Not provided.	Not provided.	200 kW per pump unit
Bladder tank	1	Length: 2.8 m Width: 1.2 m Height: 2.0 m	1 026 kg + foam agent = approx. 3 300 kg	None
Foam-proportioning equipment (connected to the tank above)	1	Width: 62 mm Height: 260 mm	16 kg	None
Deluge valves, including shut-off valves (Note: Space requirement estimation rather than actual size)	25	Length: 1.00 m Width: 1.00 m Height: 2.00 m	Approx.: 100 kg = approx. 2 500 kg	None

15.8.4 *Water curtains cost estimation*

The cost for the pipe-work assumed that DN100 and less sized galvanized distribution piping and DN40 and less galvanized branch lines were used. Table 32 shows the estimated cost for an installation on the RoPax reference ship.

Table 32: The equipment, material and labour costs associated with the system using water curtains.

	Quantity or man hours	Cost per quantity or man hour (Euro)	Total cost (Euro)
Water pump units, 5 800 litre/min @ 10 bar	2	€ 40 000	€ 80 000
Deluge valves, 6” (DN 150) including main control shut-off valves and all associated equipment	8	€ 2 500	€ 20 000
Data and supply cables	1 500	€ 15	€ 22 500
Control panels	2	€ 2 500	€ 5 000
Pipe-work (distribution pipes) with couplings and pipe hangers	1 000	€ 25	€ 25 000
Pipe-work (branch lines) with couplings and pipe hangers	500	€ 10	€ 5 000
Drainage valves and any other system valves	25	€ 15	€ 375
Open nozzles	60	€ 10	€ 600
Engineering, documentation, commissioning and any training	400	€ 100	€ 40 000
Total cost for equipment, material and engineering			**€ 198 475**
Labour cost for the installation work (estimated excluding travels, allowance, etc.)	1 500	€ 80	**€ 120 000**
Overall cost			**€ 318 475**

The footprint, weight and power demand of the equipment associated with the water supply for the system using water curtains is given in Table 33.

Table 33: The footprint, weight and power demand of the equipment associated with the water supply, etc. for the system using water curtains.

Type of equipment	Number of items	Dimensions [m], each item	Weight [kg], each item	Power demand [kW]
Water pump units, 5 800 litre/min @ 10 bar each	2	Not provided.	Not provided.	160 kW per pump unit
Deluge valves, including shut-off valves (Note: Space requirement estimation rather than actual size)	8	Length: 1.00 m Width: 1.00 m Height: 2.00 m	Approx.: 100 kg = approx. 800 kg	None

15.9 Discussion

A discussion of the cost of the identified relevant alternative fire-extinguishing systems follows below, based on comments from the system suppliers and from a ship owner’s perspective, for the different systems.

15.9.1 *Results and comments from the system supplier*

When comparing CAFS and the foam-water sprinkler and foam-water spray systems, it is likely that CAFS will be the most expensive of the three. Partly, this is due to the cost of the foam generating units and the assumptions that they are fully redundant. A cost reduction may be possible with a less stringent redundancy requirement. It is also noted that quite large system piping needs to be used, despite the relatively lower water flow rate requirement of CAFS. This is because finished foam is transported in the system piping. A 60-minute foam discharge duration requirement was applied as there are no relevant guidelines for the specific fire hazards on ro-ro spaces. However, as a 1% admixture of foam agent likely can be used, this requirement would have limited influence on the overall cost.

It can also be emphasized that CAFS technology is new in relation to sprinkler and foam system technology, which may increase the cost level as the system components are not equally standardized.

A foam-water sprinkler system will be less expensive than a foam-water spray system as it requires a lower water flow rate, which corresponds to small water pumps, less amount of foam agent and a smaller foam agent Bladder tank.

It should be underlined that the cost for a fire detection system was not include in the cost estimations. It was supposed that a fire detection system was available and that the fire detection sections correspond with the deluge systems of the foam-water spray and CAF systems, respectively. If this is not the case on an existing ship, the cost for these two systems will be correspondingly higher.

The foam-water spray system would require the highest power demand due to the largest water flow rate followed by the CAFS, as electric power is required both to pump water and to generate the foam with compressed air.

Some aspects on the system installations were raised by the system suppliers:

- The use of galvanized system piping is no longer recommended for on-shore applications due to experienced problems with internal corrosion. Black steel piping is preferred over internally galvanized piping in dry- or pre-action systems.
- Experience from Sweden and Norway does also indicate that internally galvanized piping should be avoided in wet-pipe systems due to a probability for formation of hydrogen, which may result in a pressure build-up inside piping (leading to damaged couplings) and even explosions if the hydrogen leaks out and ignites.
- Rolled groove fittings should be avoided in dry- or pre-action systems due to problems with internal corrosion.
- For dry-pipe or pre-action sprinkler installations, application of nitrogen instead of compressed air inside the pipe-work can dramatically improve the lifespan of the system. The nitrogen may be generated by a nitrogen generator or be stored in compressed nitrogen cylinders. A nitrogen generator requires a compressed air source of at least 8.6 bar (125 psi) for the membranes to operate, which is usually an air compressor provided with the generator. Systems utilizing compressed nitrogen cylinders provide the same result, but many building owners have safety concerns with high pressure cylinders in their buildings.
- The use of a foam agent can increase the risk for internal pipe corrosion and residues of foam may be very difficult to flush out from system piping after an intentional or unintentional system discharge.
- Wet, dry-pipe or pre-action sprinkler installations are typically installed with a smaller number of sprinkler sections in on-shore applications. Typically, each floor space (in this case each ro-ro space) would constitute of one section only. This would dramatically reduce the installation cost for these types of systems. For the RoPax reference ship case, a wet-, dry- or pre-action sprinkler system would only require 4 sections instead of 25 sections.

The systems using water curtains is the least expansive of the four systems in the study, however, as previously said in the study, this system cannot be considered a stand-alone system.

The cost estimation for the fire-fighting systems was made using a RoPax reference ship, however, the cost can be extrapolated to other ships given that the ratio of the number of nozzles and sections are reasonably similar, say between ±20%. For the RoPax reference ship this figure is 815 nozzles divided by 25 sections = about 33±6. Using this approach, the cost per installed sprinkler or nozzle could be summarized in accordance with Table 34.

Table 34: An approximate cost figure for the discussed system given that the ratio of the number of nozzles and sections are 33±6.

System	Approximate cost per installed sprinkler or nozzle
CAFS	€ 1 120
Foam-water sprinkler system	€ 780
Foam-water spray system	€ 865

15.9.2 *Comments from a ship owner (Stena Rederi)*

The systems described above seem to have minor impact on the ship from a technical point of view. The required power supply is around 100 kW to 200 kW and considering that no drencher pumps will need to be used at the same time (except possibly for the water curtain system) this can be handled.

Additional equipment will always be a challenge to fit onboard and some ships will be more difficult than others, but in general it should be possible to find space for this equipment onboard. The weight of the systems is noted but not considered in any loss of cargo calculations.

The potential internal pipe corrosion problems associated with the use of foam is a concern and this will most likely increase control, inspection and maintenance work and perhaps impede the function of the system over time.

For the foam systems there is a fear of creating a higher threshold for (manual) fast activation as compared to a pure water spray system. Cargo will be affected, the cleaning procedure will be more time demanding and the crew will know this is a “one shot system”, all this possibly leading to a hesitation to engage the system to only when absolute necessary, meaning the system would be operated at a later stage of the fire. When interpreting results of fire testing this expected delay in activation shall be kept in mind.

A huge concern with the system using water curtains is that it requires cargo separation to such extent there will be a large loss of cargo space. When spacing the curtains, it is favourable to have a free space of two standard length cargo units between each separation area (note, not measured centre to centre in the separation area). This is however difficult since all ro-ro ships carry different type of cargo and hence a standard-length cargo unit does not exist. Setting a figure here, for example 36 m (assuming cargo unit length in Europe 16 m to 18 m), it is likely that many vessels will experience more loss of cargo space than the actual separation area would imply. Additionally, the shape of the ship and its layout makes it more sensitive to the cargo space loss, see the example of the RoPax reference ship deck 4 in Figure 23.

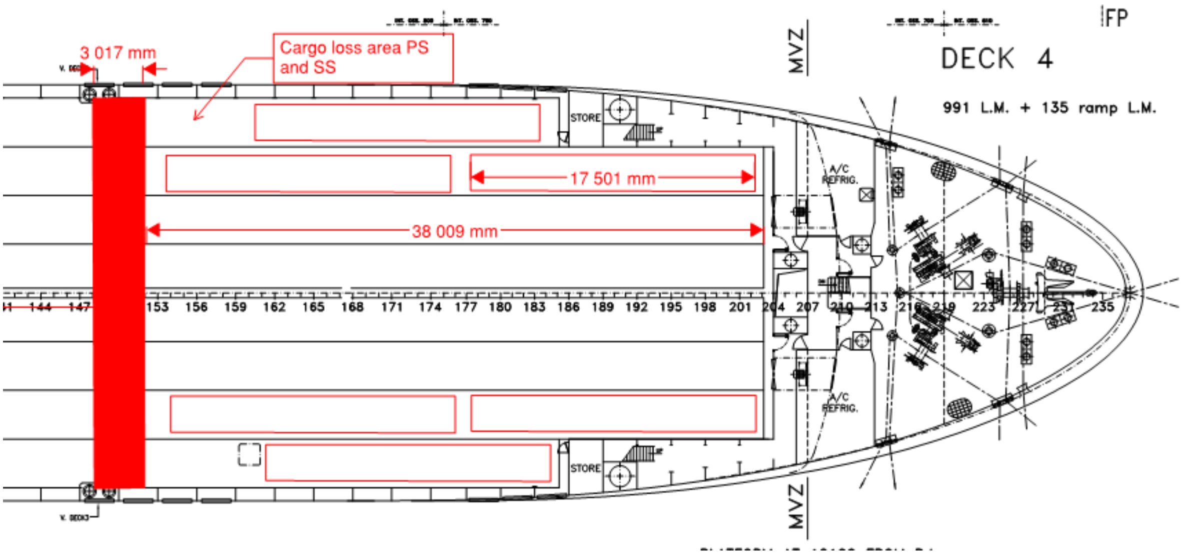

Figure 23: An example of the loss of cargo space when using water curtains.

In the Lower Hold (deck 1) there will be one separation dividing the space fairly in the middle lengthwise when applying the guidance above. Considering the shape of the space and the fact that there is a hoistable car deck (deck 2) in this space it is difficult to estimate the loss of cargo. The space would need one water curtain mounted below the hoistable deck and one water curtain mounted in the lower hold deck head. It could, however be discussed whether it is the length of the hold that shall govern the need for a curtain. Since this hold is narrower than the full beam of the ship, its total undivided volume is less than the subdivided volume of one section in the other decks. Meaning it could be questioned if it is necessary to subdivide the lower hold with a water curtain at all when the volume already is less than some of the subdivisions created on the other decks with this method. Perhaps a volume measurement would also be applicable to design a relevant water curtain system.

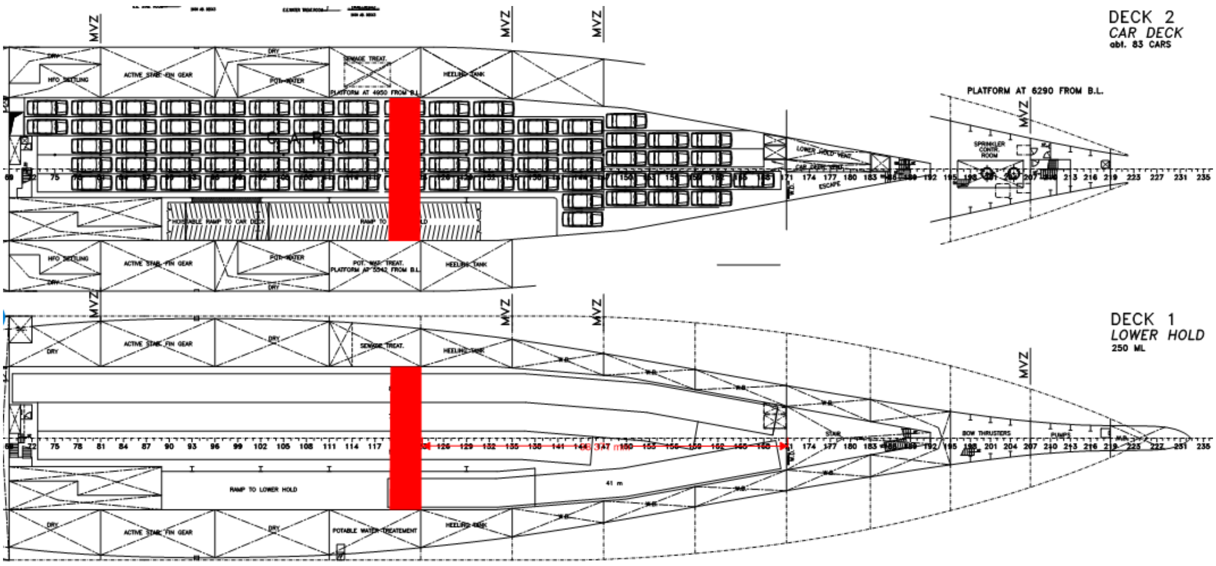

Figure 24: The arrangement of the water curtains on deck 1 and deck 2, respectively on the RoPax reference ship.

When looking at the loss of cargo space due to heavily changed and restricted cargo holds like this the loss experienced will be very different depending on the mix of cargo. To illustrate this, two examples are created with varying cargo length of 15 m and 17.5 m, respectively, but with the separation distance as proposed above of around 36 m. This results in a loss of 16 + 11 + 3 units = 30 units using the shorter cargo and 4 + 6 + 3 units = 13 units for the longer cargo units. Knowing ships sail with a mixed cargo the truth will probably lay somewhere in between these figures. Perhaps slightly on the higher side since this comparison did not consider some pre-existing paths with no cargo today, such as access to pilot gate and some ramp structure that will interfere a bit. The yearly loss of income due to the loss of cargo in monetary terms has been estimated to € 2 320 000 when considering the filling grade of the vessel over a year.

Losses due to the time-consuming loading operation has not been accounted for. But one shall note it will be much more challenging and time consuming to load the ship trying not to lose too much cargo.

15.9.3 *The cost for upgrading current fire-fighting systems onboard ships*

The main benefit of a fire-fighting system using foam would be the improved performance on fuel spill fires. The foam will spread over the surface and suppress or even fully extinguish such fires. Foam will also provide protection against fire re-ignition.

For the foam-water sprinkler and foam-water spray systems included in the study, the cost estimations indicate that the cost for the foam equipment and the actual foam is approximately 10% of the total cost for equipment and material and approximately 5% of the total installation cost of a system.

The total cost increase for an upgrade with foam (if made during the design phase) of a deluge, wet-, dry- or a pre-action system in accordance with MSC.1/Circ.1430 would therefore be relatively small if the approach in NFPA 16 of discharging foam for the initial 10 minutes is adopted. It should be noted that the discharge densities for the mentioned system types is higher in MSC.1/Circ.1430 than the discharge densities recommended in NFPA 16, as previously discussed in the report which would result in a larger sized Bladder tank.

An upgrade of a deluge system in accordance with Resolution A.123(V) on an existing ship may be conducted by installing a Bladder tank and foam-proportioning equipment, while maintaining the pump unit and the system piping. This upgrade would also require a change of the nozzle to a make and model that is approved with the specific foam agent that is chosen. Based on the cost figures given in the section, it is estimated that the cost for such an upgrade for the RoPax reference ship would be in the order or € 90 000.

An upgrade of a deluge system in accordance with Resolution A.123(V) that also include a higher discharge density is judged so be so extensive that most parts of the system need to be replaced, i.e. that the cost estimations in this section would be valid.

16 COST-EFFECTIVENESS ASSESSMENT OF SELECTED SYSTEMS

As indicated in section 13.4 and Appendix A2, no clear positive quantitative risk reduction induced by the selected systems could be retrieved from the test results. In this context, the performance of a quantitative cost-effectiveness assessment was discarded, but below follows a brief discussion on the efficiency of the systems in relation to the estimated costs.

The large-scale fire tests showed that the risk reduction potential induced by adding foam to a water spray system designed in accordance with Resolution A.123(V) is likely small. However, as estimated in 15.10.3, the marginal cost of the implementation of this system would also be quite low, both on new-built and existing ships. Considering the potential additional improved performance of using a foam water-based system on fuel spill fires, it could be speculated that the system would still reach the cost-effectiveness threshold.

The large-scale fire tests showed that performance of CAFS in simulated closed and open ro-ro spaces was poorer than of the system designed in accordance with Resolution A.123(V). This would lead to a negative risk reduction, rendering the cost-effectiveness assessment irrelevant. Furthermore, the tested CAFS implied a significantly increased cost, which would preclude this system from reaching cost-effectiveness even if performing as well as a conventional system (or if accounting for potential superior performance on a flammable liquid spill fire). Hence, even if a different design of the CAFS would provide improved performance leading to a potential overall risk reduction equal to 0, the system would still not be cost-effective, unless the cost of implementation of such system would be significantly decreased. It should be noted that this result applies particularly to closed and open ro-ro spaces and not to other applications of CAFS, e.g. on weather deck.

17 IDENTIFICATION OF REGULATORY BARRIERS

Based on the discussion above, no system was recommended to be required to replace current systems, but it was considered relevant to investigate whether foam-water sprinkler or foam-water spray systems could be applied onboard ro-ro passenger ships and if not, how regulations could be revised to allow such a system.

As per the current regulations, it was interpreted as acceptable to install a fixed foam-water fire-extinguishing system onboard ro-ro passenger ships for the purpose of complying with the requirements of SOLAS II-2/6. In particular:

- SOLAS II-2/20.6.1.2 requires that "Vehicle spaces and ro-ro spaces not capable of being sealed and special category spaces shall be fitted with a fixed water-based fire-fighting system for ro-ro spaces and special category spaces complying with the provisions of the Fire Safety Systems Code which shall protect all parts of any deck and vehicle platform in such spaces."
- The FSS Code, Ch.7 §2.4, as amended, specifies that this fixed water-based fire extinguishing system has to comply with MSC.1/Circ.1430.
- MSC.1/Circ.1430 covers fixed water-based fire-fighting systems, including foam fire-fighting systems as indicated in MSC.1/Circ.1430, §3.19: "Any foam concentrates used as system additives should comply with the Revised Guidelines for the performance and testing criteria and surveys of foam concentrates for fixed fire-extinguishing systems (MSC.1/Circ.1312)."

Consequently, a fixed foam-water sprinkler or spray fire-extinguishing system may be installed in ro-ro spaces on passenger ships, provided it is in line with MSC.1/Circ.1430 and especially:

- The foam concentrate has to be approved as per MSC.1/Circ.1312.
- The application rate has to be either:
    - In line with the values given in MSC.1/Circ.1430, Tables 4-1, 4-2 and 4-3 for prescriptive-based systems; or
    - Determined through the fire tests described in MSC.1/Circ.1430 for performance-based systems - if potential benefits from a foam-water sprinkler or foam-water spray system on Class B fires (not included in the prescribed fire tests) are to be considered, e.g. with the ambition to reduce the system discharge rate, approval could be made through SOLAS II-2/17 Alternative design and arrangements.

18 DISCUSSION

The results of the study are discussed in themes, divided accordingly in sections below.

18.1 Upgrading of fire-extinguishing systems on existing ships

Existing ships with ro-ro spaces having a manually operated deluge water spray system in accordance with Resolution A.123(V) could probably relatively easily be upgraded to a traditional automatic wet-, dry- or pre-action sprinkler system in accordance with MSC.1/Circ.1430. The water flow requirements for such systems are typically lesser and the sprinkler pump capacity and power demand requirements could likely be fulfilled, although new system piping would need to be installed. The improvements with an automatic system in terms of earlier activation and fire suppression performance would be significant with such an upgrade.

The performance of systems in accordance with Resolution A.123(V) could also be improved, especially for flammable liquid spill fires, by the use of a foam agent. The upgrade would require foam proportioning equipment and a foam agent tank, but all other parts of the system can remain unaltered.

The use of an approved alternative fire protection system (currently typically a water mist system), tested and installed in accordance with the requirements in MSC.1/Circ.1430, would require an investment of a new sprinkler pump unit and the power demand may be a concern. For a low-pressure water mist system, it may be possible to use the existing piping, but for a high-pressure system this would not be possible. A certain performance improvement would be expected with a wet- or dry-pipe system as earlier activation would be accomplished. However, it should be regarded that the overall performance of a deluge system is relatively similar to the performance of a system installed in accordance with the former lower prescriptive performance standard as per Resolution A.123(V).

18.2 Specific hazards associated with alternative fuel vehicles

Despite the specific fire hazards that were identified with new energy carriers, these vehicles share many characteristics with traditional vehicles. Time is critical and limiting the damage and stopping the fire development early is important to prevent severe consequences.

Preferably, a fire should be suppressed before it damages the fuel storage (the battery pack, the gas tank, etc.) of the vehicle and before it spreads to an adjacent vehicle. This can be done in most fire scenarios if fire detection is sufficiently early and if the right (manual) fire-fighting equipment and strategy is used. However, manual fire-fighting strategies are out-of-the scope of this project.

Ethanol is very similar to the conventional energy carriers; however, a fuel spill fire could be more difficult to extinguish. Foam agents need to be alcohol resistant to perform properly. On the other hand, an ethanol spill fire may be diluted by the application of large amounts of water. From that perspective, a spill fire in ethanol could be considered less hazardous as compared to traditional fuels as petrol and diesel, which are not possible to dilute with water.

The application of water from over-head sprinklers or nozzles could prevent fire spread between vehicles, limit the fire growth rate and protect the space from heat damages as well as scrubbing the air from harmful combustion products. The scrubbing effect of Hydrogen fluoride (HF) gas is an area for future research discussed elsewhere in the report. Water from over-head sprinklers or nozzles may not be able to extinguish a fire inside a vehicle and if that fire affects the fuel storage there might still be severe consequences from the fire.

18.3 Fire suppression of ordinary combustibles with traditional sprinklers and water mist

Two relevant research projects, the IMPRO-project conducted by RISE and a project conducted by FM Global, were identified where fire suppression of ordinary combustibles with water spray and water mist nozzles has been studied. The conclusions of the projects are similar; fire suppression is primarily affected by the application density and spray characteristics, such as droplet size, discharge velocity and spray thrust force, not by nozzle configuration or operating pressure. In both projects, fire suppression in open environment with water mist required water densities higher or comparable to those of water spray nozzles or sprinklers. However, a benefit with water mist is the improved reduction of the convective heat release rate for shielded fires, which underlines the improved cooling efficiency of the smaller water droplets. In summary, the experience from these projects indicates that a water mist system with a high discharge density (significantly higher than the alternative systems currently approved for ro-ro spaces in accordance with MSC.1/Circ.1430) is suitable, as it would provide both fire suppression, excessive cooling of hot gases as well as heat radiation attenuation. It is recommended that fire tests study the ability of water spray or water mist systems in preventing a large, shielded vehicle fire from spreading to adjacent vehicles and from one deck to the deck above.

For fire control or fire suppression of flammable liquid spill fires, the use of a foam additive would improve the performance considerably.

18.4 Alternative fire-extinguishing systems identified in the project

The project focused on identifying alternative fire-extinguishing systems to the systems that are already recognized in SOLAS. The following three alternative fire-extinguishing systems were identified:

1. Compressed Air Foam Systems (CAFS).
2. Foam-water sprinkler and foam-water spray systems.
3. Water curtains.

The first two are commercially available but not recognized for the protection of ro-ro spaces. The third is not commercially available and there is no established installation or testing standards. Furthermore, water curtains were not considered possible to replace a conventional fixed fire-extinguishing system, as this solution would be more suitable for sub-division and containment than extinguishment.

Furthermore, the project looked the potential fire performance capabilities of the fire-extinguishing systems discussed in the report. The performance was expressed using three different performance objectives; fire control, fire suppression and fire extinguishment. A fixed-pipe CAF system would offer several benefits as compared to traditional foam-water sprinkler and foam-water spray systems, for example an improved penetration of the fire plume, a better fuel-vapor barrier and longer burn-back time for flammable liquid spill fires, better thermal radiation protection as the foam blanket stays in place for extended periods of time on top of a fuel and sticks to vertical surfaces, and a reduction of the quantity of water and foam concentrate. However, the literature survey has not identified any direct fire test data for the ro-ro space application that supports how these systems should be designed and installed.

Traditional foam-water sprinkler and foam-water spray systems would improve the performance against flammable liquid spill fires as compared to a traditional water spray deluge system. The use of a foam agent additive may also have some benefits for solid combustible fires, as it blocks heat radiation which prevents or limits fire spread.

Limited test data is available for water curtains. The test data indicate that water curtains may be used to sub-divide a space by limiting the heat radiation and the cooling of hot combustion gases. However, the available test data show that water flow rates probably need to be high. If used on a ro-ro space, water curtains need to be supplemented by any of the other fire-extinguishing systems discussed in the report in order to control, suppress or extinguish a fire.

18.5 The installation cost of the alternative fire-extinguishing systems

The installation costs for CAFS, a foam-water sprinkler and foam-water spray as well as a system using water curtains was estimated based in input from system suppliers. The results indicate that CAFS is the most expensive of the three. A system with water curtains is the least expensive, but the areas sub-divided by the water curtains require a “firebreak”, i.e. a horizontal safety distance spacing of cargo. This distance results in a loss of cargo space that is associated with a significant yearly loss in income for a ship owner.

18.6 Large-scale fire tests

Two alternative, commercially available fixed fire-extinguishing systems was selected for the large-scale fire tests; a foam-water spray system and a CAF system. The fire suppression performance of the two systems was compared to the performance of a deluge water spray system designed in accordance with Resolution A.123(V) and MSC.1/Circ.1430, respectively. The former is commonly used on existing ships, the latter is used on ships constructed after 2012.

The fire scenario used in the tests simulates a partly shielded (to the water spray) and partly exposed fire in a freight truck trailer.

It can be concluded that the deluge water spray system designed in accordance with MSC.1/Circ.1430, that discharged 10 mm/min of plain water had a superior performance. The discharge density of 5 mm/min associated with the system designed in accordance with Resolution A.123(V) limited the fire, but not to a level where fire spread to a space above or to adjacent vehicles definitely can be judged to be prevented. The performance of the foam-water spray system was more or less between the two water spray systems, which is in line with the discharge density of 6.5 mm/min. There are limited signs of performance improvements due to the use of the foam additive, however for a potential fire scenario that also is involving a spill fire, improvements of using foam are likely to be achieved.

Two tests were conducted with the CAF system. One test with an unaltered fire test set-up and one test where the fire scenario was fully exposed, less amount of combustibles was used and with an earlier system activation. Both fire tests were terminated as limited fire suppression was observed. Part of the reason for the system performance is probably that the discharge density of 2.4 mm/min is significantly less compared to the other systems. It is, however, worth noting that the particular CAF systems used in the tests is approved for flammable liquid fuel fires and that normally the extinguishing mechanism is creating a physical barrier to suppress vapours and reduce the amount of oxygen. For the type of fire present for this test series more work would be needed to find a recipe that would create more of a cooling effect while keeping the advantages of the CAF bubbles. CAF distribution can also be modified to apply the CAF in the areas that are more critical. The advantage of CAF is that it can be adjusted and modified to suit the different needs since it is created at the system and the recipe can be changed and tailored for different applications.

18.7 Risk reduction by the selected systems

Part of the objective of the project was to determine the expected risk reduction of the selected systems in relation to a conventional ‘drencher’ system designed and installed in accordance with Resolution A.123(V). The large-scale fire tests showed that the foam-water spray system performed better than the water spray system designed in accordance with Resolution A.123(V), both in terms of improved fire control capabilities and in terms of reduced surface temperatures on a fictive, adjacent vehicle. The performance of the CAFS was, as previously discussed, poorer than the system designed in accordance with Resolution A.123(V).

The fire scenario used in the tests simulates a partly shielded (to the water spray) and partly exposed fire in a freight truck trailer. All dimensions of the test set-up except for the overall length are realistic and the system nozzles were installed to simulate an actual fire suppression installation in terms of nozzle height, nozzle clearance and nozzle spacing. The fire scenario can be considered fully realistic but does not include any flammable liquid spill fires. For a multi-fire scenario that involves ordinary combustibles as rubber tires, plastic parts on the exterior of a vehicle, the interior of a vehicle and the cargo on a freight truck trailer combined with flammable liquid spill fires, originating from for example a damaged fuel tank, broken hydraulic hoses, windshield wiper fluid it is no doubt that the use of foam will provide additional performance improvements that were not captured by the tests.

It should be noted that the both the foam-water spray system and the CAFS that was used in the tests were approved for flammable liquid hazards. It is expected that both systems would provide superior performance on a flammable liquid spill fire. As a matter of fact, the foam-water spray system was tested with an alcohol resistant foam concentrate that would be applicable for use with new energy carriers containing Ethanol or any other alcohol. Regarding the use of foam, it is important to point out that the make and model of the nozzle that is used is approved with the specific foam agent that is chosen.

19 AREAS FOR FUTURE RESEARCH

This section summarises issues where additional research is desired based on this report. The list of issues is not complete but covers the main issues that have been identified in this part of the project.

19.1 Activation of automatic sprinklers or nozzles

The activation of automatic sprinklers or nozzles (i.e. sprinklers or nozzles that are activated by the heat from a fire) could be severely influenced by the deckhead construction. For unobstructed ceiling constructions, the general recommendation in sprinkler installation standards is that the vertical distance between the sprinkler deflector and the ceiling/deckhead shall be a minimum of 25 mm and a maximum of 305 mm.

Sprinklers or nozzles at the underside of 'obstructed ceiling constructions' need to be positioned such that the ceiling construction in terms of beams, trusses, flanges or other members does not affect the water distribution. On the other hand, a vertical distance too far from the deckhead will influence the activation time.

The problem of fulfilling both these recommendations in ro-ro spaces, where deep beams and wide flanges are common, has been recognized by several Member States.

It is recommended that this issue is studied in detail. It may be that the certain types of ceiling constructions require installation of a (light-weight) non-combustible, flat and smooth false ceiling under the load bearing construction to enable the activation of automatic sprinklers or nozzles.

19.2 Revision of the fire test procedures of MSC.1/Circ.1430

The current study indicated that fire test procedures in MSC.1/Circ.1430 for alternative fixed fire-extinguishing systems need to be revised, primarily as the fire scenarios are not reflecting the severity and fire load of real case vehicle fires and because the performance requirements are related to the former lower prescriptive performance level of systems in accordance with Resolution A.123(V).

There are also concerns that the repeatability and reproducibility of the fire tests are poor. It can be concluded that this may partly explain the notable design differences in terms of water discharge densities for the approved systems.

19.3 Scrubbing effects of Hydrogen fluoride (HF) in sprinkler water sprays

One concern identified with fires involving Li-ion batteries is the large amount of Hydrogen fluoride (HF) gas that could be contained in the combustion gases.

Hydrogen fluoride is a highly dangerous gas, forming corrosive and penetrating hydrofluoric acid upon contact with moisture. The gas may immediately and permanently damage lungs and can also cause blindness by rapid destruction of the corneas [48]. The IDLH value (Immediately Dangerous to Life and Health) is only 30 ppm [49].

As the battery pack of vehicles are well shielded from direct application of a water spray from over-head sprinklers or nozzles, a fire involving a battery pack will not be suppressed or controlled. However, the water spray may be able to scrub out HF in gas form and transform it to Hydrofluoric acid and dilute it to a concentrate that is less hazardous.

It should be noted that Hydrofluoric acid is a highly corrosive liquid and a powerful contact poison. Because of the ability of hydrofluoric acid to penetrate safety gear/clothing and tissue, poisoning can occur readily through exposure of skin or eyes, or when inhaled or swallowed. Symptoms of exposure to hydrofluoric acid may not be immediately evident and this can provide false reassurance to victims, causing them to delay medical treatment [48].

19.4 Design of high-expansion foam systems

These systems have several benefits that are interesting for ro-ro space applications. An effective fill-up of foam of the entire protected space would be an effective means of controlling a fire, especially as foam with the right properties' spreads across a fuel surface and around obstacles. Additional research on the application, especially for inside-air systems, is desired to verify that such systems are suitable for the protection of ro-ro spaces.

20 CONCLUSION

Three alternative fire-extinguishing systems were identified for the protection of ro-ro spaces: Compressed Air Foam Systems (CAFS), Foam-water sprinkler and foam-water spray systems, as well as Water curtains. The first two systems are commercially available but not recognized for the protection of ro-ro spaces. A system relying on water curtains is not commercially available and there is no established installation or testing standards. Furthermore, water curtains were not considered possible to replace a conventional fixed fire-extinguishing system, as this solution would be more suitable for sub-division and containment than extinguishment.

All the alternative solutions were theoretically evaluated in terms of performance capability and water consumption, taking in account typical fire hazards in ro-ro spaces and specific hazards associated with alternative fuel vehicles. It was concluded that traditional foam-water sprinkler and foam-water spray systems would improve the performance against flammable liquid spill fires as compared to a traditional automatic sprinkler or deluge water spray systems. The use of a foam agent additive may also have some benefits for solid combustible fires, as it blocks heat radiation which prevents or limits fire spread. A fixed-pipe CAFS may offer several benefits as compared to traditional foam-water sprinkler and foam-water spray systems, for example improved penetration of the fire plume, a better fuel-vapor barrier and longer burn-back time for flammable liquid spill fires, better thermal radiation protection as the foam blanket stays in place for extended periods of time on top of a fuel and sticks to vertical surfaces, and a reduction in the quantity of water and foam concentrate. However, the literature survey did not identify any direct fire test data for the ro-ro space application that supports how these systems should be designed.

Despite the specific fire hazards that were identified with new energy carriers, these vehicles share many characteristics with traditional vehicles. Time is critical and limiting the damage and stopping the fire development early is important to prevent severe consequences. Ethanol and other bio-fuels or blends with petrol containing alcohols are very similar to conventional energy carriers; however, a fuel spill fire could be more difficult to extinguish. Foam agents need to be alcohol resistant to perform properly. On the other hand, an ethanol spill fire may be diluted and neutralized by the application of large amounts of water. From that perspective, a spill fire in ethanol could be considered less hazardous compared to traditional fuels such as petrol and diesel, which are not possible to dilute with water. The application of water from over-head sprinklers or nozzles could prevent fire spread between vehicles, limit the fire growth rate and protect the space from heat damages as well as scrub the air from harmful combustion products. The scrubbing effect of Hydrogen fluoride (HF) gas is an area for future research. Water from over-head sprinklers or nozzles may not be effective to extinguish a fire inside a vehicle and if that fire involves the fuel storage there may still be severe consequences from the fire.

Comparing the installation cost of CAFS and the foam-water sprinkler and foam-water spray systems, it is likely that CAFS will be the most expensive of the three. Partly, this is due to the cost of the foam generating units and the assumptions that they should be fully redundant. A cost reduction may be possible with a less stringent redundancy requirement. It can also be emphasized that CAFS technology is new in relation to a traditional foam system technology, which may increase the cost level as the system components are not equally standardized. A system with water curtains is the least expensive, but the areas sub-divided by the water curtains require a “firebreak”, i.e. a horizontal safety distance spacing of cargo. This distance results in a loss of cargo space that is associated with a significant yearly loss in income for the ship owner.

The large-scale fire tests showed that a deluge water spray system designed in accordance with MSC.1/Circ.1430, discharging 10 mm/min of plain water, had a superior performance. A discharge density of 5 mm/min, associated with the system designed in accordance with Resolution A.123(V), limited the fire but not to a degree where fire spread to a space above or to adjacent vehicles could definitely be judged to be prevented. The foam-water spray system had a discharge density of 6.5 mm/min and the performance was more or less between the two water spray systems. The improvement compared to the system designed in accordance with Resolution A.123(V) were likely mainly due to the increased discharge rate. However, for a potential fire scenario that also involves a spill fire, improvements of using foam could be relevant. Both CAFS fire tests were terminated since only limited fire suppression was observed. Part of the reason for the relatively poor performance of the system is probably that the discharge density of 2.4 mm/min was significantly less compared to that of the other systems.

Areas for future research include testing of the activation of automatic sprinklers or nozzles (i.e. sprinklers or nozzles that are activated by the heat from a fire) at the underside of ‘obstructed ceiling constructions’, revision of the fire test procedures in MSC.1/Circ.1430, testing of any scrubbing effects by sprinkler water sprays on Hydrogen fluoride (HF) generated in fires involving Li-ion batteries, and additional research on the application of high-expansion foam systems, especially inside-air systems.

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22 LIST OF ABBREVIATIONS

AFV:	Alternative Fuel Vehicles
BEV:	Battery Electric Vehicles
BLEVE:	Boiling Liquid Expanding Vapour Explosion
BV:	Bureau Veritas
CAF:	Compressed Air Foam
CAFS:	Compressed Air Foam Systems
CCTV:	Closed-circuit television
CEP:	Cartoned Expanded Plastic
CNG:	Compressed Natural Gas
CO_2:	Carbon Dioxyde
EMSA:	European Maritime Safety Agency
FP:	Sub-Committee on Fire Protection
FSS:	Fire Safety Systems (Code)
HEV:	Hybrid Electric Vehicles
HF:	Hydrogen Fluoride
HFCV:	Hydrogen Fuel Cell Vehicles
HRR:	Heat Release Rate
IACS:	International Association of Classification Societies
IDLH:	Immediately Dangerous to Life and Health
IMO:	International Maritime Organization
Li-ion:	Lithium-ion
Li-salt:	Lithium-salt
LNG:	Liquefied Natural Gas
LPG:	Liquefied Petroleum Gas
MSC:	Maritime Safety Committee
MVZ:	Main Vertical Zone
NFPA:	National Fire Protection Association
NiMH:	Nickel Metal Hydride
PGA:	Pyrotechnically Generated Aerosols
PRV:	Pressure Relief Valve
SOLAS:	International Convention for the Safety Of Life At Sea
SSE:	Ship Systems and Equipment (IMO Sub-Committee)
tPRD:	Temperature-controlled Pressure Relief Device

A1 LIST OF PARTICIPANTS IN SELECTION OF SYSTEMS

In order to cover wide spectrum of expertise, eight participants participated to the workshop on April 17, 2018 for the identification of alternative fixed fire-extinguishing systems and the selection of relevant systems.

The list of the participants as well as their areas of expertise are presented below:

From Stena:

- Lisa Gustin (Naval Architect)
- Joacim Lottkärr (Master Mariner)

From Bureau Veritas:

- Jérôme Faivre (Rules Development Engineer)
- Jérome Leroux (Risk Analysis Engineer)

From RISE:

- Magnus Arvidson (Research Scientist in Fire Fighting)
- Franz Evegren (Research Scientist in Fire Safety Engineering)
- Pierrick Mindykowski (Research Scientist in Fire Safety Engineering)
- Roeland Bisschop (Fire Safety of new energy carriers)

A2 FIRE TESTS OF ALTERNATIVE FIRE-EXTINGUISHING SYSTEMS

The conducted fire tests are described below, by first describing the fire test set-up and the systems tested, followed by the instrumentations and the fire test procedures used. The results of the tests are then described in graphs and also in photos, before the test results are discussed and concluded.

A2.1 The fire test set-up

The fire test set-up consisted of a trailer mock-up with simulated cargo, as further described below.

A2.1.1 The trailer mock-up

The mock-up was constructed to geometrically replicate a typical freight truck trailer, except that the overall length was shorter than in reality. Table A2-1 shows the dimensions and typical dimensions of actual freight truck trailers.

Table A2-1: The dimensions of the trailer mock-up as compared to the maximum dimensions stipulated in Directive (EU) 2015/719 (which amends Directive 96/53/EC).

Dimensions	Dimensions of the trailer mock-up [m]	Dimensions of an actual freight truck trailer [m]
Length	3.6	12.0*
Width	2.6	2.55* – 2.60**
Overall height	4.0	4.0*
Internal height of cargo space	2.8	2.65 – 2.80***
Height of cargo platform above ground	1.1	1.0 – 1.2

*) The maximum dimensions stipulated in Directive (EU) 2015/719 (which amends Directive 96/53/EC).
**) Maximum width of superstructures of conditioned vehicles.
***) Typical height for standard trucks and trailers, however “Mega” trucks may have cargo spaces of up to 3.05 m - 3.10 m.

In Europe, heavy goods vehicles, buses and coaches must comply with certain rules on weights and dimensions for road safety reasons and to avoid damaging roads, bridges and tunnels. Directive (EU) 2015/719 sets maximum dimensions and weights for international traffic. Relevant figures are provided in the table. Sweden and Finland have an exception to the directive which allows freight trucks with trailers to be a maximum of 25.25 m long. In addition, it is common that the freight trucks are up to 4.50 m high in these countries.

The mock-up was constructed from 50 mm square iron and the bottom and the roof of the platform of the mock-up was constructed from nominally 4 mm and 3 mm thick steel plates, respectively. The vertical supports and the square iron construction for the roof had hose connections and was cooled by water during the tests to allow the construction to be re-used in the test series. Water was injected at the bottom of the left-hand side vertical supports and ejected at the bottom of the right-hand side vertical supports.

Four rows of commodity (see a detailed description below) were positioned on the platform such that longitudinal and transversal gaps of 100 mm were created between the stacks of commodity, see Figures A2-1 and A2-2.

Figure A2-1: An illustration of the arrangement of the commodity on the trailer mock-up, the roof over the central 2 by 2 stacks of commodity and the steel screens alongside the set-up.

Figure A2-2: The trailer mock-up from another view that shows the Industrial Calorimeter.

Four fire tests were conducted with the test set-up described above, however, due to the results in Test 4, the test set-up was altered for Test 5. The modifications included a removal of the roof over the central part of the array and the outmost stacks of commodity on either side was not used. This provided for a fully exposed fire and less combustible loading. The intent of this test set-up was to offer additional test data with the CAF system. Figure A2-3 shows the test set-up.

Figure A2-3: The altered test set-up used in Test 5, where the roof over the central 2 by 2 stacks of commodity was removed and the outmost stacks of commodity not were used.

A2.1.2 The target screens

Vertical steel screens were positioned parallel with the long sides, respectively, of the trailer mock-up at a horizontal distance of 0.6 m. This distance is representative for the typical distance between vehicles on a ro-ro space. The screens had a height (2.8 m) that corresponded to the height of the 'cargo space' of the mock-up. The tops of the screens were levelled with the top level of the roof that partly covered the trailer mock-up, i.e., 4.0 m above floor level. The length of 1.8 m was shorter than the overall length of the mock-up but covered the two 2 by 2 stacks of commodity. A horizontal part of the screens having a width of 0.6 m simulated the top part of an adjacent vehicle.

The surface temperatures of the steel screens were measured at eighteen (18) different measurement points, see the description under "Instrumentation and measurements". The nominal thickness of the steel sheets used for the screens was 1.5 mm and the front face of the screens were painted black using heat-resistant paint.

A2.1.3 The commodity

The EUR Std Plastic commodity consists of empty Polystyrene (PP) cups without lids, placed upside down (i.e. open end down), in compartmented cartons, 120 cups per carton. The cartons measure 600 mm × 400 mm × 500 mm (L × W × H) and are made from single-wall, corrugated cardboard. When compartmented, the cartons are divided into five layers using corrugated sheets, with each layer divided into 24 compartments by over-locking corrugated cardboard partitions, forming a total of 120 compartments where the plastic cups are placed.

When used on standard 1200 mm × 800 mm EUR pallets, eight cartons are placed on each pallet. The overall dimension of one pallet load is consequently 1200 mm × 800 mm × 1000 mm (L × W × H) plus the height of the pallet (nominally 150 mm). The commodity contains 960 polystyrene cups per pallet load. The commodity is shown in Figure A2-4.

The individual cups have a measured average weight of 28.2 g, correlating to a total weight of the plastic of 3.4 kg per carton. The overall weight of one carton including the cups is approximately 5.4 kg. The total weight (excluding the pallet) of one 1200 mm × 800 mm pallet load of the commodity is approximately 43.2 kg of which approximately 63% by weight was plastic, excluding the pallet. If the weight of the wooden pallet is included in this estimation, approximately 42% by weight is plastic.

Figure A2-4: One pallet load of the EUR Std plastic commodity (left) with a close-up photo of the arrangement of the plastic cups in the individual cartons (right).

When developed, the intention was to make the EUR Std Plastic commodity as similar as possible to the FM Global Std Group A Plastic commodity, i.e. using the same type materials, approximately the same overall size, the same number of cups, the same density of plastic, etc. However, the commodity had to fit the pallet size dimensions used within Europe. Because of the different geometry of the cartons, as compared to the 'original' commodity, the plastic cups had to be made slightly smaller and lighter, although the cup was designed for approximately the same wall and bottom thickness as the FM Global cup. The amount of plastic per pallet load of commodity is, however, identical. The FM Global Standard Plastic Commodity and the FM Global Class II Commodity have been widely used in the fire protection community as two representative "benchmark" warehouse fire hazards for evaluation of sprinkler fire protection performance in large-scale fire tests since the 1970's. The FM Global Class II Commodity consists of double triwall cartons with a steel liner inside. Non-combustible products in slatted wooden crates are defined as Class II commodities. In this case, the packaging is contributing to the combustibility of the commodity. By contrast, the packaging may limit the involvement of the material inside. Exposed plastic commodities, for example, require higher sprinkler densities than the same plastic contained in corrugated cartons since the cartons absorb sprinkler water and delay involvement of the plastic material.

Although the EUR Std Plastic commodity does not represent the most severe commodity that can be found on a freight truck trailer in practice (commodities containing for example expanded plastics, as upholstered furniture, are regarded as more severe), it was considered representative of a high hazard commodity. The fact that it is established as a "benchmark" commodity in large-scale sprinkler fire tests made it logical to use in these tests.

For the tests, cartons were placed on a standard EUR wood pallet and the individual cartons were stapled against the wood pallet to increase stability. Two pallets loads were positioned on top of each other which equalled an overall height of approximately 2.3 m. The vertical distance measured from the top of the commodity to the underside of the roof of the trailer mock-up was 0.5 m.

A2.2 The fire suppression systems

The tested systems are described below by first describing the objectives behind using the different systems, the general pipework and then the technical details of the systems used.

A2.2.1 The fire test program

The fire test program included the following systems:

1) **A water spray system as per the prescriptive requirements in MSC.1/Circ.1430.** This test established the performance of a modern water spray system installed onboard ships built after 2012. The system used open water spray nozzles and discharged 10 mm/min of plain water.
2) **A water spray system as per Resolution A.123(V).** This is the benchmark system that represent the performance of water spray systems onboard existing ships. The system used open water spray nozzles and discharged 5 mm/min of plain water.
3) **A foam-water spray system.** The system used open non-air aspirating, low-expansion foam nozzles and discharged 6.5 mm/min of Class B foam. The design density was adopted from the requirements in NFPA 16 and foam was discharged for 10 minutes, followed by plain water. The primary advantage of foam-water spray and foam-water sprinkler systems over conventional water-based fire extinguishing systems, without the use of a foam agent, is the improved performance on flammable liquid pool fires, i.e. Class B fires. For ro-ro spaces, where flammable liquid spill fires may be directly shielded from the over-head application of water spraying sprinklers or nozzles, foam may offer a significant performance improvement. Use of foam can also boost the systems' capabilities of dealing with fires in solid combustibles, i.e. Class A fires. It is particularly effective at handling fires in polymers, e.g. plastics, which melt, drip, and subsequently form pool fires.
4) **CAFS.** The system used rotating nozzles and discharged 2.4 mm/min of Class B foam. A fixed-pipe CAF system would offer several benefits for the protection of ro-ro spaces, for example improved penetration of the fire plume and thermal radiation protection as the foam blanket stays in place for extended periods of time on top of a fuel and sticks to vertical surfaces. However, the literature survey did not identify any direct fire test data for the ro-ro space application that supports how these systems should be designed (foam type, foam quality, discharge densities, discharge duration times, etc.) and installed (over-head nozzles only or over-head nozzles combined with pop-up nozzles, nozzle coverage areas, etc.).

Table A2-2 summarizes the fire test parameters.

Table A2-2: The systems and system parameters used in the tests

Test	Type of system	Standard	Nominal discharge density [mm/min]	Type of nozzles	Nozzle spacing	Type of foam
1	Water spray	MSC.1/Circ.1430	10 mm/min	Open water spray	3.2 m x 3.0 m	None
2	Water spray	Resolution A.123(V)	5 mm/min	Open water spray	3.2 m x 3.0 m	None
3	Foam-water spray	NFPA 16	6.5 mm/min	Low-expansion foam nozzle	3.2 m x 3.0 m	Class B
4	CAFS	NFPA 11	2.4 mm/min	Rotary CAFS nozzle	3.2 m x 3.0 m	Class B
5	CAFS	NFPA 11	2.4 mm/min	Rotary CAFS nozzle	3.2 m x 3.0 m	Class A

A2.2.2 The system pipe-work

The piping arrangement for the systems consisted of a balanced tree system. The system had four DN25 (1") branch lines with nozzle connections for four nozzles at a 3.2 m (W) × 3.0 m (L) nozzle spacing, i.e. a coverage area of 9.6 m^2 per nozzle. The system was fed through a fire hose that was connected to the public main via a constant-pressure valve (Tests 1 and 2), a frequency-controlled pump unit (Test 3) or directly to the CAFS equipment (Tests 4 and 5). The pipe-work and the position of the nozzles relative to the trailer mock-up is shown in Figure A2-5.

Figure A2-5: The pipe-work its support beams. The support beams were insulated to protect them from thermal exposure

The vertical distance measured from the nozzles to the roof of the trailer mock-up was 0.5 m and the vertical distance to the top of the stacks of commodity approximately 1.0 m. Photo: RISE.

A2.2.3 A description of the tested systems

The water spray system

The water spray system used open (non-automatic), pendent directional discharge medium velocity water spray nozzles. The nozzles had an external deflector that discharged a uniformly filled cone of medium velocity water droplets. The nozzles used in the tests had no nozzle strainer. Figure A2-6 illustrates the nozzles.

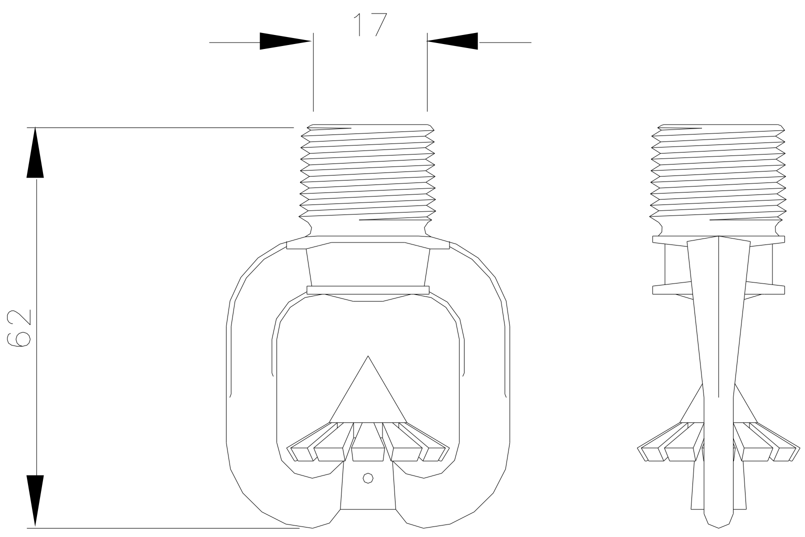


Figure A2-6: A principle drawing of the open (non-automatic) medium velocity nozzles used with the water spray system. The actual nozzles used in the test have a horizontal, flat deflector. Illustration: TYCO Fire Suppression & Building Products.

The nozzles are available in a wide variety of orifice sizes and spray angles, however, the types listed in Table A2-3 were used during these tests.

Table A2-3: The water spray nozzles that were used, their orifice diameter, corresponding K-factor, spray angle and the system parameters used in the tests.

Nozzle designation	Minimum orifice diameter [mm]	Nozzle K-factor	Nozzle spray angle [°]	Nominal discharge density [mm/min]	System operating pressure [bar]	Flow rate per nozzle [litre/min]	Total system flow rate [litre/min]
D3, No. 24	8.3	43.2	180	5	1.2	48	192
D3, No. 32	11.1	80.6	180	10	1.4	96	384

The recommended discharge pressures range from 1.4 bar to 4.1 bar. Discharge pressures in excess of 4.1 bar will result in a decrease in coverage area since the spray pattern tends to draw inwards at higher pressures. The maximum recommended working pressure is 12.1 bar.

The nozzles were installed with their frame arms parallel with the longitudinal flue between the trailer mock-up and the steel sheet screens on either side.

The foam-water spray system

The foam-water spray system used open (non-automatic) non-air aspirating, low-expansion foam nozzles. The nozzles are fitted with a wire mesh below and at the side of the external deflector where the foam was formed. The nozzles discharged a uniformly filled cone of low-density foam over a large coverage area. The foam expansion ratio is approximately 6 – 8, depending on the K-factor of the nozzle, the operating pressure and the type of foam that is used. The nozzles used in the tests had a K-factor of 57 and were considered standard-coverage nozzles. The nozzles had no nozzle strainer. Figure A2-7 shows the nozzle.

Figure A2-7: The open (non-automatic) non-air aspirating, low-expansion foam nozzle used in Test 3. Photo: Jomos Eurosprinkler AG.

The nozzles were installed with their frame arms parallel with the longitudinal flue between the trailer mock-up and the steel sheet screens on either side.

A foam-water spray system should be designed for a discharge rate of at least 6.5 mm/min if designed in accordance with NFPA 16 and this recommendation was used in the test. The corresponding flow rate per nozzle was 62.4 litre/minute and the nominal system operating pressure 1.2 bar. The total flow rate of the four installed nozzles was 250 litre/min. For these tests, an alcohol-resistant fluorine-free fire extinguishing foam concentrate was used at a concentration of 3%.

The foam was discharged for 10 minutes, followed by a 20-minute discharge of plain water. The foam discharge duration time was adopted from NFPA 16.

The expansion ratio of the foam was measured during the test and confirmed to be around 6:1.

The CAF system

A complete system including the compressed air supply equipment, the water control valve, the stainless-steel foam tank and a mixing chamber was used in the tests. All parts of the system were pre-assembled and ready to be connected to the fixed pipe-work via a hose. CAF is formed by combining air under pressure, water and a foam concentrate in the right proportions and the foam is a substance resembling shaving cream and is composed of extremely small bubbles. These bubbles give the solution stream a very large surface-to-mass-ratio thus absorbing heat very effectively. Foam suppresses a fire by forming a physical barrier on the surface of the fuel. This barrier blocks the heat of the flames from further fuelling the fire and also reduces the amount of oxygen available to the fire.

It should be noted that CAF is carried using standard piping network as used for conventional sprinkler or foam systems, however, finished foam is transported in the piping. To distribute the CAF over the hazard area, nozzles specifically developed for CAF are used to insure a proper distribution of the compressed air foam over the protected area. These nozzles are offered in different types for different applications. For these tests, a rotary type nozzle with a large coverage area was used. Figure A2-8 shows the nozzles.

Figure A2-8: The rotary type CAFS nozzle used in Tests 4 and 5, respectively. Photo: FireFlex Systems Inc.

For Test 4, a 3x3 AFFF multipurpose film forming foam was used. It shall be used at 3% concentration on both hydrocarbon and polar solvents fires using fresh, brackish or seawater and this concentration was used in the test. The agent was PFOS free.

For Test 5, a Class A foam was used. The recommended proportioning rate for CAFS is 0.1% - 0.5%. However, for this test an approximate concentration of 1% was used. The foam is fluorine-free. The intent was to discharge foam for the full 30-minute duration of the test, however, none of the tests lasted that long.

Figure A2-9 and A2-10, respectively, shows the distribution of the foam over the test set-up during distribution test prior Test 4.

Figure A2-9: A CAF distribution test prior Test 4 confirmed a uniform distribution of foam over the test set-up.

Figure A2-10: A close-up illustration of one of the rotary CAF nozzles during the distribution test prior Test 4.

A2.3 Instrumentation and measurements

The instrumentation and measurements made are described in detail below.

A2.3.1 The Industrial Calorimeter

The tests were conducted under the Industrial Calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire. The hood is 6 m in diameter with its lower rim 7.2 m above the floor. For these tests, a cylindrical fibreglass ”skirt”, hanging from the lower rim of the hood, was used to increase the gas collecting capacity of the hood. In the duct connecting the hood to the evacuation system, measurements of gas temperature, velocity and the generation of gaseous species such as CO_2 and CO and depletion of O_2, can be made.

Based on these measurements, both the convective and the total heat release rate can be calculated, as described below.

HRRconv: The convective heat release rate measured during a test is calculated on the basis of the gas temperature and mass flow rate in the calorimeter system. The convective fraction of the total heat release varies with the fuel and other factors, but usually approximately two-thirds of the energy generated by a fire is released through convection. Additionally, the convection produces the velocities and temperatures in the fire plume. The velocity and temperature in the fire plume determines the rate of heat transfer, i.e., the convective heat release rate is also responsible for the activation of sprinklers and the heating of the overhead ceiling or deck. The maximum convective heat release rate is, therefore, one of the most important quantities for characterising fire severity.

HRRtot: The total heat release rate measured during a test is calculated on the basis of the oxygen depletion of the fire, as measured in the calorimeter system. HRRtot is comprised of both the convective and radiative heat release rate, as well as the heat being conducted away and absorbed within the test set-up. During the fully developed stage of a fire, however, heat conduction and absorption is relatively small compared to the convective and radiative components. Radiation is the primary mechanism by which fire spreads across aisles and other open spaces to adjoining combustibles. It is also, in part, responsible for lateral fire spread throughout a large fuel array, as well as an overall fundamental measure of fire severity.

A2.3.2 Surface temperature measurements

The surface temperatures of the steel plates positioned along both long sides of the trailer mock-up were measured at eighteen (18) different measurement points, on each of the steel plates. Three of the measurement points were positioned on the horizontal top surface of the steel plate and the remaining fifteen measurement points on the vertical surface facing the trailer mock-up.

The measurements were made with (Type K) thermocouples having a diameter of 0.5 mm that were spot-welded directly to the back side of the steel plate. All the temperature measurement points and the associated channels are shown in Table A2-4.

Table A2-4: The temperature measurement points and the associated channels.

Measurement channels		Position
Right hand side screen	Left hand side screen	
C21	C41	Horizontal top surface
C22	C42	Horizontal top surface (midline)
C23	C43	Horizontal top surface
C24	C44	Vertical surface, 150 mm below top
C25	C45	Vertical surface, 150 mm below top (midline)
C26	C46	Vertical surface, 150 mm below top
C27	C47	Vertical surface, 775 mm below top
C28	C48	Vertical surface, 775 mm below top (midline)
C29	C49	Vertical surface, 775 mm below top
C30	C50	Vertical surface, 1400 mm below top
C31	C51	Vertical surface, 1400 mm below top (midline)
C32	C52	Vertical surface, 1400 mm below top
C33	C53	Vertical surface, 2025 mm below top
C34	C54	Vertical surface, 2025 mm below top (midline)
C35	C55	Vertical surface, 2025 mm below top
C36	C56	Vertical surface, 2650 mm below top
C37	C57	Vertical surface, 2650 mm below top (midline)
C38	C58	Vertical surface, 2650 mm below top

A2.3.3 System water pressure and water flow rate measurements

The system water pressure upstream of the solenoid valve of the pipe-work using a Transinstrument 2000A pressure transducer. The total water flow rate was measured using a Krohne 0 – 2000 L/min flow or a Krohne 0 – 200 L/min flow meter (the CAFS tests).

A2.4 The fire test procedures

The fire test procedures are described below, divided on the fire ignition source and the used testing procedures.

A2.4.1 The fire ignition source

The commodity was ignited at the flue, near the bottom of the central 2 by 2 stacks of commodity using four standardised ignition sources positioned directly against the corrugated cartons. The ignition source consists of a cube, 60 mm × 60 mm × 75 mm, made from pieces of insulating fibre board. Each cube was soaked with 120 mL of heptane and wrapped in a polyethylene plastic foil bag prior to the test. Figure A2-11 shows the positions of the ignition sources.

Figure A2-11: The standardised igniters that consisted of a cube made from pieces of insulating fibre board soaked with heptane and wrapped in a polyethylene plastic foil bag, positioned near the bottom of the central 2 by 2 stacks of commodity.

A2.4.2 Fire test procedures

The fire suppression systems were manually activated at a convective heat release rate of 3 MW, which equalled a total heat release rate of approximately 5 MW. The heat release rate upon activation was selected to simulate a manually activated system and to allow the fire to be well established before activation, thereby avoiding any influence on system performance due to unrealistic test conditions.

The fire suppression systems were run for 30 minutes, after which the test was manually terminated, and the remaining fire manually extinguished.

A2.5 Fire test results

This section summarizes the fire tests results based on the measurements and visual observations.

Figure A2-12 shows the total heat release rate histories for Tests 1 – 4. It can be observed that the initial fire growth rate, up until the manual activation of the systems, was very similar for all fire tests indicating a good test-to-test repeatability.

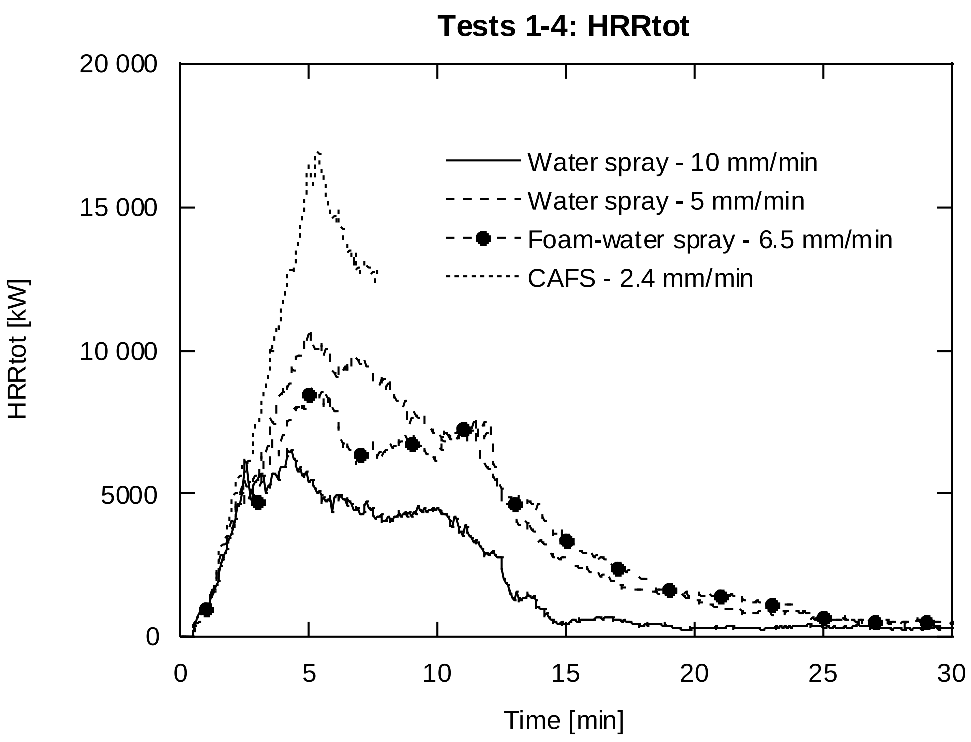


Figure A2-12: Tests 1-4: Total heat release rate histories. The CAFS test was manually terminated at the time the dotted line is cut.

Figure A2-13 shows the convective heat release rate histories for Tests 1 – 4.

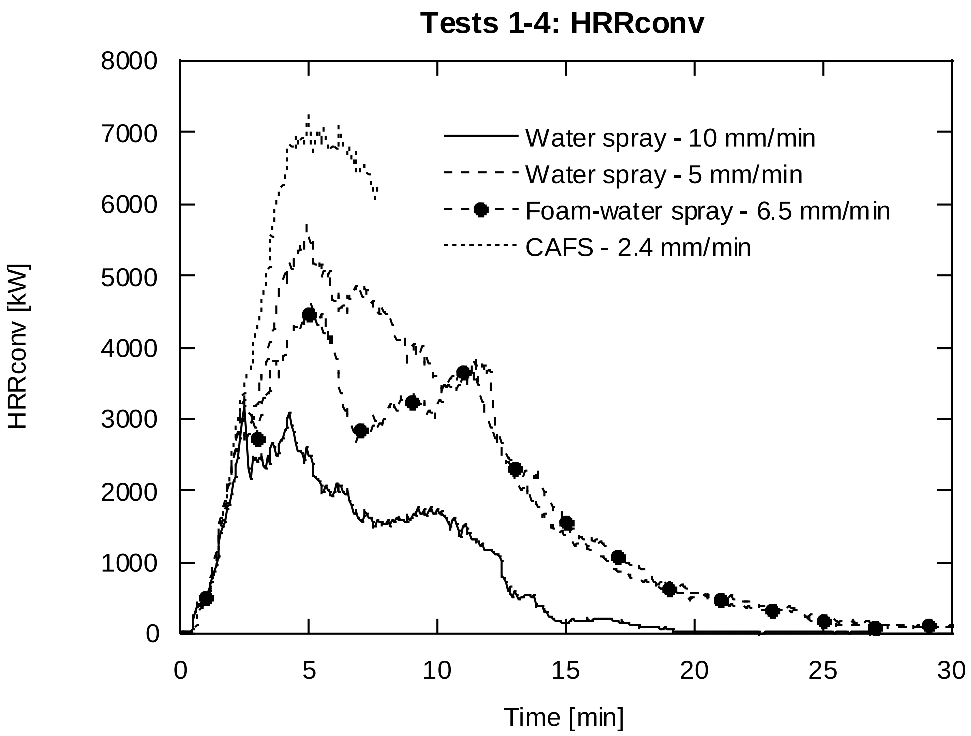


Figure A2-13: Tests 1-4: Convective heat release rate histories. The CAFS test was manually terminated at the time the dotted line is cut.

From the heat release rate histories, it can be concluded that the water spray system discharging 10 mm/min reduced the heat release rate more or less immediately after activation. The fire re-developed but the fire size did not exceed the level at the activation. Thereafter, the fire size was gradually reduced, and the fire size was limited after a 10-minute discharge.

The activation of the water spray system discharging 5 mm/min had a minor initial effect on the fire and the fire continued to grow to about 10.5 MW before it started to decline. A similar observation is made for the foam-water spray system discharging 6.5 mm/min. However, the peak heat release rate was slightly less, around 8.5 MW. The fire declined faster in this test, however, a fire re-growth is observed about 7 minutes after the start of the test.

The activation of CAFS had a limited effect on the heat release rate and the fire grew to a level that required a manual intervention of the test. The heat release rate had started to decline, probably as the combustibles of the central 2 by 2 stacks of commodity started to be consumed when the fire test was manually terminated.

Figure A2-14 shows the mean temperature for all measurement points on the target steel sheet screens for Tests 1 – 4.

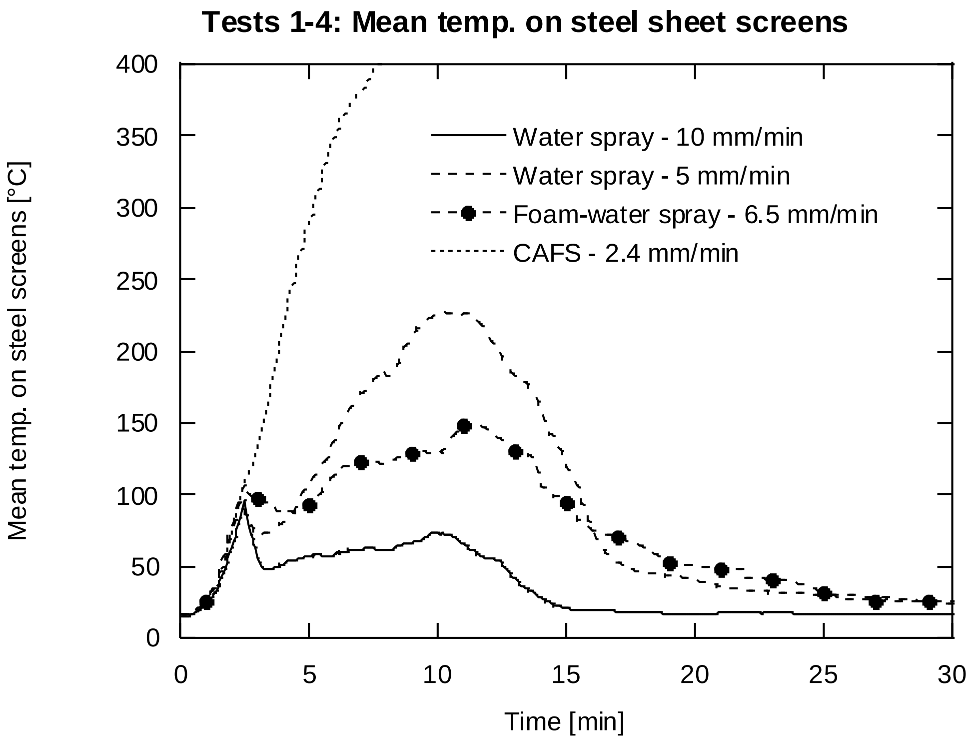
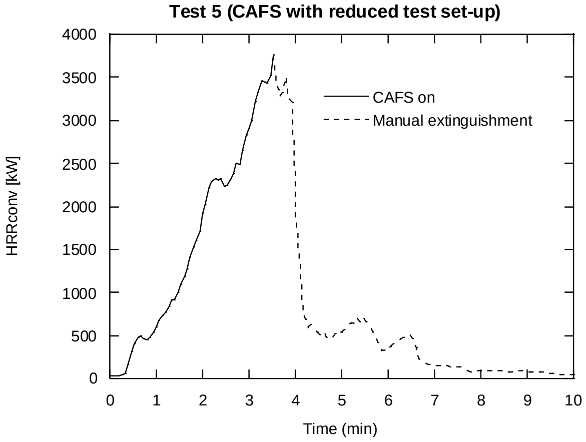


Figure A2-14: Tests 1-4: The mean temperature on the steel sheet screens. The CAFS test was manually terminated at the time the dotted line is cut.

The trends of the mean temperature on the steel sheet screens follows the trends of the heat release rate measurements and directly correlates to the water discharge densities of the systems. The peak levels associated with the water spray system discharging 10 mm/min is very moderate and fire spread to an adjacent vehicle seems unlikely. Fire spread does also seem unlikely for the foam-water spray discharging 6.5 mm/min although the mean temperature is higher. For the water spray system discharging 5 mm/min, the mean surface peaked around 230°C and fire spread to adjacent vehicles may well be possible.

The activation of CAFS had a limited effect on the mean temperature on the steel sheet screens.

Figure A2-15 shows the convective heat release rate histories and the mean temperature on the steel sheet screens for the CAFS tests in Test 5. Due to the severity of the fire in Test 4, the measurement equipment was partly damaged which prevented the measurement of the total heat release rate. The CAF system was manually activated at 02:12 [min:sec] at a convective heat release rate of approximately 2.3 MW, i.e. slightly lower than in Test 4. The test was terminated at 03:26 [min:sec] when it was judged that the system had limited effect on the fire event.



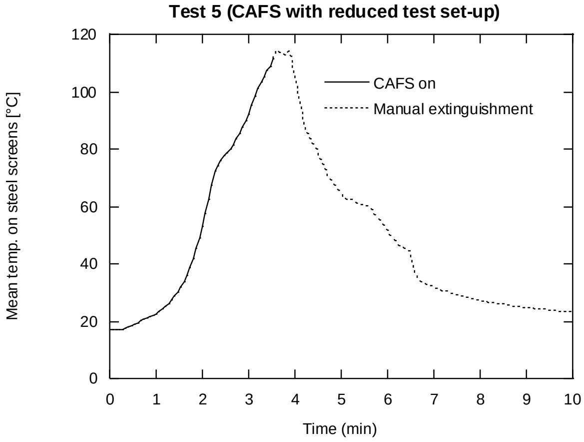


Figure A2-15: Tests 5: Convective heat release rate history and the mean temperature on the steel sheet screens for the second CAFS test. The test was manually terminated at the time the solid line is cut and the dotted line captures manual fire extinguishment.

A2.6 Photos from the tests

Figures A2-16 through A2-20 shows selected photos from the tests.

Two minutes after system activation. Three minutes after system activation.

Ten minutes after system activation. Thirteen minutes after system activation.

Figure A2-16: Test 1: Photos illustrating the fire event.

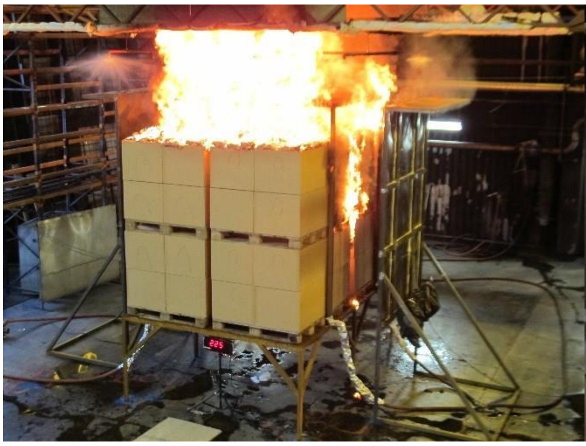
System activation.

One minute after system activation.

Five minutes after system activation.

15 minutes after system activation.

Figure A2-17: Test 2: Photos illustrating the fire event.



System activation.

Five minutes after system activation.

10 minutes after system activation.

15 minutes after system activation.

Figure A2-18: Test 3: Photos illustrating the fire event.


System activation.

Two minutes after system activation.


Five minutes after system activation.

Six minutes after system activation.

Figure A2-19: Test 4: Photos illustrating the fire event. Photo: RISE.

System activation. One minute after system activation.

Two minutes after system activation, manual extinguishment has been initiated. Three minutes after system activation, continued manual extinguishment after system shut-off.

Figure A2-20: Test 5: Photos illustrating the fire event.

A2.7 Discussion and conclusion

The main objective was to evaluate the fire suppression performance of two alternative, commercially available fixed fire-extinguishing systems having the potential to be used for ro-ro spaces on ro-ro passenger ships; 1) a foam-water spray system and 2) a Compressed Air Foam System (CAFS). The fire suppression performance of the two systems was compared to the performance of a deluge water spray systems designed in accordance with Resolution A.123(V) and MSC.1/Circ.1430, respectively. The former is commonly used on existing ships, the latter is used on ships constructed after 2012.

The fire scenario used in the tests simulates a partly shielded (to the water spray) and partly exposed fire in a freight truck trailer. All dimensions of the test set-up except for the overall length are realistic and the system nozzles were installed to simulate an actual fire suppression installation in terms of nozzle height, nozzle clearance and nozzle spacing. The test set-up resembles the one used in the IMPRO-project, however, the combustible loading was less. The heat release rate of the fire was measured, and the steel sheet screens instrumented with thermocouples simulated adjacent vehicles to where the fire could potentially “spread”.

It can be concluded that the deluge water spray system designed in accordance with MSC.1/Circ.1430, that discharged 10 mm/min of plain water had a superior performance. The fire size was controlled, and the fire control capabilities and direct cooling of the steel sheet screens would likely have prevented fire spread to adjacent vehicles. The discharge density of 5 mm/min associated with the system designed in accordance with Resolution A.123(V) limited the fire, but not to a level where fire spread to a space above or to adjacent vehicles definitely can be judged to be prevented.

The performance of the foam-water spray system was more or less between the two water spray systems, which is in line with the discharge density of 6.5 mm/min. There are limited signs of performance improvements due to the use of the foam additive, however for a potential fire scenario that also is involving a spill fire, improvements of using foam are likely to be achieved.

Two tests were conducted with the CAF system. One test with an unaltered fire test set-up and one test where the fire scenario was fully exposed, less amount of combustibles was used and with an earlier system activation. Both fire tests were terminated as limited fire suppression was observed. Part of the reason for the system performance is probably that the discharge density of 2.4 mm/min is significantly less compared to the other systems. It is, however, worth noting that the particular CAF systems used in the tests is approved for flammable liquid fuel fires and that normally the extinguishing mechanism is creating a physical barrier to suppress vapours and reduce the amount of oxygen. For the type of fire present for this test series more work would be needed to find a recipe that would create more of a cooling effect while keeping the advantages of the CAF bubbles. CAF distribution can also be modified to apply the CAF in the areas that are more critical. The advantage of CAF is that it can be adjusted and modified to suit the different needs since it is created at the system and the recipe can be changed and tailored for different applications.

A2.8 Acknowledgement

The FIRESAFE II consortium would like to thank the manufacturers who provided equipment, support and technical advice for the fire tests: TYCO Fire Suppression & Building Products (Sweden), Jomos Eurosprinkler AG (Switzerland), Dr. R. Stahmer GmbH & Co. KG (Germany), FireFlex Systems Inc. (Canada), Dafo Fomtec AB (Sweden).