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LASH FIRE

Deliverable D11.2

Development of means for subdivision of ro-ro spaces

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Abstract

A ro-ro space on a ro-ro ship offers great flexibility by providing substantial large spaces for stowage of goods. The major benefits of a ro-ro space unfortunately also entail the major fire challenge, namely that they extend to a substantial or entire length of the ship. Barriers are essential to avoid longitudinal fire and smoke spread to the same extent.

The goal of this report was to assess the development for vertical subdivision of ro-ro spaces. The conducted studies have considered smoke, fire, and heat integrity as well as regulatory, integration and cost aspects. and contribute to the objective to develop and demonstrate artificial and new means for fire integrity subdivision of ro-ro spaces.

Two different types of subdivisions were developed and evaluated: water curtain and fabric curtain. Both solutions have potential to function as a containment measure but show challenges for implementation on board.

Water mist is undoubtedly a powerful solution for fire suppression and control. However, some weaknesses inherent to the application of water curtains were identified during the reduced scale study, namely smoke destratification, turbulent mixing promoting some fire increase in some cases, smoke flow through the water curtain after its activation, increase of the smoke exhaust at the side openings within the contained space. At this stage the use of water mist seems to induce a cost increase for a benefit which is still questionable within the present application.

Fabric curtain is used in building applications and was evaluated for usage on board. Both reduced-, and large-scale tests show that a curtain that is fully rolled down results in most effective subdivision in terms of smoke shielding. The advantage of a partly rolled down curtain that does not reduce cargo loading space, is not obtained.

On board assessments were used to evaluate feasibility for subdivision with the use of fabric curtains on board vessels. Installation on board is challenging however, both for technical and cost reasons.

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Involved partners

No.	Short name	Full name of Partner	Name and contact info of persons involved
01	RISE	RISE Research Institutes of Sweden AB	Anna Olofsson, anna.olofsson@ri.se David Schmidt Pierrick Mindykowski Kim Olsson, kim.olsson@ri.se Magnus Bobert, magnus.bobert@ri.se Örjan Westlund, orjan.westlund@ri.se
04	FLOW	FLOW Ship Design DOO za Projektiranje, Konzalting I Inzenjering u Brodogradnji	Vito Radolovic, vito.radolovic@flowship.eu Obrad Kuzmanovic, obrad.kuzmanovic@flowship.eu
05	MAR	Marioff Corporation Oy	Antti Virkajärvi, antti.virkajarvi@carrier.com
08	BV	Bureau Veritas Marine & Offshore Registre International de Classification de Navires et de Plateformes Offshore	Blandine Vicard, blandine.vicard@bureauveritas.com Jérome Leroux
18	LUL	Université de Lorraine	Rabah Mehaddi, rabah.mehaddi@univ-lorraine.fr Davood Zeinali, davood.zeinali@risefri.no Pascal Boulet, pascal.boulet@univ-lorraine.fr

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Content

1 Executive summary

1.1 Problem definition

A ro-ro space is normally extending for a considerably length of the vessel or in some cases across the whole length of the ship. This provides the operator much flexibility for stowing of goods which could be cars, trucks, containers, or other bulk cargo and is essential for the purpose of a ro-ro ship, i.e. to roll on and roll off the cargo. The wide and long ro-ro spaces is a challenge when looking from a fire spread perspective. Due to the lack of subdivision of the space a fire is allowed to spread from cargo to cargo in worst case along the whole vessel.

Subdivisions to divide a ro-ro space is studied in this deliverable. Two different types of vertical subdivisions are developed and evaluated: water curtain and fabric curtain.

1.2 Method

The alternatives for subdivision of ro-ro spaces were evaluated from a theoretical and regulatory view. Solutions were categorized in water curtain and fabric curtain and differentiation between the two main categories were tested in reduced scale tests. On board assessments were used to evaluate feasibility for subdivision with the use of fabric curtains on board vessels. Large scale experiments were conducted for striped fabric curtain partly and fully rolled down.

1.3 Results and achievements

Water mist is undoubtedly a powerful solution for fire suppression and control. However, some weaknesses inherent to the present application were identified during the reduced scale study, namely smoke destratification, turbulent mixing promoting some fire increase in some cases, smoke flow through the water curtain after its activation, increase of the smoke exhaust at the side openings within the space. At this stage the use of water mist seems to induce a cost increase for a benefit which is still questionable within the present application.

Both reduced-, and large-scale tests show that a curtain that is fully rolled down results in most effective subdivision in term of smoke shielding. The advantage of a partly rolled down curtain that does not reduce cargo loading space, is not obtained. The project proposes one solid curtain to subdivide a ro-ro space to be a rational solution, and to have it installed in line with a drencher zone. For ship integration, this solution is found challenging but feasible for newbuildings ro-pax and ro-ro cargo ships. Due to the need of a free space in a straight line for rolling down the curtain the loss of cargo/revenue is a cost driven item.

There are no guidelines regulating water or fabric curtain design and performance currently available. If curtains are to be implemented in ro-ro spaces, standards and test protocols need to be developed.

1.4 Contribution to LASH FIRE objectives

Outcome from this report contribute to evaluations of new means for fire integrity and subdivision of ro-ro spaces. The report relates to action 11-A *Division of ro-ro spaces* and provides results for the effectiveness of subdivision of ro-ro space with different curtain solutions.

1.5 Exploitation

The result from this report will present the effect of developed solution for subdivision of ro-ro space. End users will get insight of the challenges related to implementation of the solution on board and what to consider designing a subdivided ro-ro space. Suppliers will get insight in the negative effect of gaps between curtains and protected area. Research institutes and University departments can use test data for validation of smoke and heat spreading in a ship environment.

2 List of symbols and abbreviations

AFV	Alternative fuelled vehicle
CCTV	Closed Circuit Television
FTP	International Code for the Application of Fire Test Procedures
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
IACS	International Association of Classification Societies
IMO	International Maritime Organization
MAV	Moving Average
MLR	Mass Loss Rate
MSC	Maritime Safety Committee
MVZ	Main Vertical Zone
SOLAS	International Convention for the Safety of Life at Sea
WP	Work Package

3 Introduction

Main author of the chapter: Pierrick Mindykowski, RISE and Antti Virkajärvi, MAR.

A ro-ro space on a ro-ro ship offers great flexibility by providing substantial large spaces for stowage of goods. The major benefits of a ro-ro space are also the major fire challenge, namely that they extend to a substantial or entire length of the ship. Barriers are essential to avoid longitudinal fire and smoke spread to the same extent.

The goal of this report it to assess the development for vertical subdivision of ro-ro spaces. This report includes the description of development and the tests used to evaluate the selected solutions. Two solutions have been considered: water curtain, and a fabric curtain.

Water mist curtains is a specific application developed to subdivide a space to prevent fire and heat from travelling from the location of origin to adjacent areas. Water mist droplets discharged vertically downward at high pressure have properties enhancing the performance of a water curtain:

- water mist droplets block radiant heat effectively.
- evaporation of water mist droplets cools down hot combustion gases.
- high velocity water mist discharge brings combustion gases down from ceiling level and mixes them with surrounding air thus preventing them from travelling along the ceiling.
- water mist curtain is not a solid barrier allowing firefighting crew to walk through an active water mist curtain.

Water mist systems in general were introduced to the market in the early 1990’s. Since then the systems and also water mist standards have been going through major development, and currently water mist systems can protect all areas in buildings and in ships. The most common areas being accommodation areas and machinery spaces. In fact, the major benefit of water mist systems compared to traditional fire protection systems is that all hazard in a building or on board a ship can be protected with one firefighting system. The design and approvals of water mist systems rely on full scale fire tests. In these tests water mist systems are tested according to clearly defined and acknowledged fire test methods developed by well-known authorities for specific fire categories, such as accommodation areas (IMO Res.MSC.265(84)), machinery spaces (IMO MSC/Circ.1165) and ro-ro spaces (IMO MSC.1/Circ.1430). The performance criteria in the standards are usually based on equivalency compared to the performance of traditional fire protection systems (i.e. conventional sprinkler systems or gas systems).

Fabric curtains made of different textiles are mainly used inside buildings, for big dimensions or architectural design. They are designed to confine a volume in terms of smoke and/or fire, by closing an opening. The textile shall be certified for a fire/smoke rating. Curtains with this purpose are today seldom used on board ships.

Fabric curtains have the advantage to have a small footprint as they stay open and close only in case of necessity and have the advantage to be lighter compared to a steel rolling shutters due to lower weight. Fabric curtains are usually connected to a fire alarm and will close as soon as they receive a contact from a smoke or fire detector. In case of a power failure, a backup battery will keep the curtain open. The curtain will then close and would not be able to open without a power supply.

The first chapter hereafter provide a regulatory review concerning subdivision of ro-ro spaces, this is followed by a chapter regarding requirements for ship integration aspects. Then, one chapter is dedicated to the water curtain solutions and the next chapter is dedicated to the fabric curtain solution. Finally, conclusions for development of means for subdivision of ro-ro spaces is provided.

4 Regulation review concerning subdivision of ro-ro spaces

Main author of the chapter: Blandine Vicard and Jérome Leroux, BV.

This chapter provides an overview of the requirements currently applicable to ro-ro spaces as per the existing rules and regulations that may be related to the purpose of Action 11-A, i.e., ”Develop and demonstrate artificial and new means for fire integrity subdivision of ro-ro spaces”. Basically, this report summarizes the current requirements aimed at ensuring the fire integrity of ro-ro spaces.

4.1 Applicable regulations

The present review is based on the currently applicable regulations. Therefore, some of the requirements detailed below may not be applicable on old/existing ships. A brief summary of the main regulation changes related to division of ro-ro spaces is provided in Table 1 with a particular focus on regulations relevant to Action 11-A .

Table 1. Summary of regulation changes

Regulation change	Application date	Adoption date	Summary
SOLAS 74	1980[1]	1974	Introduces the principle of horizontal fire zone for ro-ro spaces / special category spaces with: • Structural fire protection • Fixed fire extinguishing system (“drencher” type) • Fixed fire detection system
MSC.338(91)	01/07/2014	30/11/2012	Raises the fire integrity requirements for ro-ro and vehicle spaces on board cargo and passenger ships carrying not more than 36 passengers

The review is mainly based on the documents listed in Table 2.

[1] It is to be noted that the concept of horizontal fire zone and associated safety measures has actually been introduced in SOLAS 60 part H as per IMO resolution A.122(V) dated October 1967. However, the circular was never made mandatory, and Part H was therefore only applied on a voluntary basis until SOLAS 74 came into force. Compliance with Part H is formally recognized to be equivalent with SOLAS 74.

Table 2. List of documents used for the review of regulations for Division of ro-ro spaces

IMO Documents	SOLAS Convention, as amended
	2010 FTP Code, as amended
	MSC.1/Circ.1120, Unified Interpretations of SOLAS Chapter II-2, The FSS Code, The FTP Code, and related Fire Test Procedures
	MSC.1/Circ.1615, Interim Guidelines for minimizing the incidence and consequences of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships
IACS and Class Rules	IACS Blue book dated January 2019
	BV Rules for Steel Ships (NR467), as amended in July 2019
	DNVGL Rules for the Classification of Ships, January 2017
	LR Rules and Regulations for the Classification of Ships, July 2016
Flag Administration Rules	MMF (French Flag Administration) Division 221 “Passenger ships engaged in international voyages and cargo ships of more than 500 gross tonnage”, 28/12/17 edition
	US Coast Guard Code of Federal Regulations (CFR) 46, 2019 online edition
	Swedish Transport Agency “Comments and interpretations by the Swedish Transport Agency regarding IMO Conventions”, version 03 dd.15/05/2017
	MCA (UK Flag Administration) Guidance on SOLAS Chapter.II-2

4.2 Definitions

This section provides the definitions of key terms used in regulations relevant to subdivision of ro-ro spaces.

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

As per SOLAS II-2/3:

- “*Vehicle spaces are cargo spaces intended for carriage of motor vehicles with fuel in their tanks for their own propulsion.*”
- *“Ro-ro spaces are spaces not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction.”*[2]
- *“Special category spaces are those enclosed vehicle spaces above and below the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m.”*

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

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

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

4.2.2 Closed, open and weather deck

As per SOLAS II-2/3:

- A "*weather deck is a deck which is completely exposed to the weather from above and from at least two sides.*"
  IACS UI SC 86 additionally details that: "For the purposes of Reg. II-2/19 a ro-ro space fully open above and with full openings in both ends may be treated as a weather deck."
  For practical purposes, drencher fire-extinguishing system cannot be fitted on weather decks due to the absence of deckhead. This criterion is often used for a practical definition of weather decks.
- An open vehicle or ro-ro space is "*either open at both ends or [has] an opening at one end and [is] provided with adequate natural ventilation effective over [its] entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides.*"
- A closed vehicle or ro-ro space is any vehicle or ro-ro space which is neither open nor a weather deck.
  As a reference criterion, it can be considered that a vehicle space that needs mechanical ventilation is a closed vehicle space.

4.3 Requirements

This section describes the requirements related to division of ro-ro spaces and provides the associated reference(s) in the regulatory texts.

4.3.1 General

SOLAS II-2/9 details a very comprehensive set of measures for the purpose of containing a fire on board a ship. The approach relies on a categorisation of each space, taking into account as a background both the fire risk in the space and the criticality of losing it. Basically:

- Some spaces are identified as key elements to ensure either proper fire-fighting or evacuation. Those are basically the control stations and the escape routes. Those spaces are to be preserved as much as possible from any fire.
- Other spaces are regarded as potential fire risks (with various risk levels) and the aim is to prevent a fire from spreading from and to those spaces.

Then SOLAS includes specific fire containment requirements including summary tables detailing the required level of fire integrity between spaces for the following ship categories:

- Passenger ships carrying more than 36 passengers;
- Passenger ships carrying not more than 36 passengers;
- Cargo ships other than tankers; and
- Tankers.

[SOLAS II-2/9]

Ro-ro spaces can be found on the first three types of ships. The corresponding fire containment requirements are detailed below.

4.3.2 Horizontal fire zones on passenger ships

[SOLAS II-2/2.2]

In principle, passenger ships are separated into main vertical zones, the length of which is normally limited to 40 m[3]. In order to accommodate garage spaces spanning potentially over the whole length of the ship, SOLAS II-2/20.2.2 allows the definition of horizontal zones which ”*may include special category spaces on more than one deck provided that the total overall clear height for vehicles does not exceed 10 m*[4]”. The required integrity for horizontal fire zones is the same as for main fire zones i.e.:

- A-60 fire integrity on passenger ships carrying more than 36 passengers, which may be reduced to A-0 where the space on the other side of the fire division has a very low fire risk (open decks, sanitary spaces or tanks, voids, and machinery spaces with little or no fire risk)
- A class fire integrity on passenger ships carrying not more than 36 passengers, with detailed ratings in line with Table 3.

”Main vertical zone boundary integrity” also refers to complementary requirements, especially regarding the doors leading to the ro-ro vehicle spaces including, for practical purposes, that:

- Those doors are to be self-closing
- An indication that they are properly closed is to be available in the continuously manned central control station
- Arrangements are to be made to ensure local control of the doors, including power-operated doors, also taking into account the case of a fire (door to be operable up to 200°C)

[SOLAS II-2/9.4.1.1.5]

It should also be noted that the concept of the horizontal fire zone is also associated with an efficient fire-extinguishing system.

4.3.3 Fire integrity requirements for the boundaries of ro-ro and vehicle spaces

On passenger ships carrying more than 36 passengers, the boundaries–decks and bulkheads–of ro-ro and special category spaces are required to have A-60 fire integrity. This fire integrity level may however be reduced to A-0 where the space on the other side of the fire division has a very low fire risk (open decks, sanitary spaces or tanks, voids, and machinery spaces with little or no fire risk).

[SOLAS II-2/20.5]

The fire integrity level required between ro-ro or vehicle spaces and other space on cargo ships or passenger ships carrying not more than 36 passengers is summarized in Table 3 below.

[SOLAS II-2/9 Tables 9.3, 9.4, 9.5 and 9.6]

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[3] The length and width of main vertical zones (MVZ) may be extended to a maximum of 48 m (MVZ bulkheads to coincide with watertight bulkheads) or total area of MVZ must not be greater than 1600 m2 on any deck (to accommodate large public spaces, for instance)

[4] The way to measure this 10m height is further clarified in IMO MSC.1/Circ.1120 and IACS UI SC158.

Table 3. Fire integrity requirements around ro-ro or vehicle spaces

	Space categories	**Fire integrity requirement with respect to a ro-ro or vehicle space**
Key spaces to be preserved	Control stations	A-60
	Stairways and corridors	A-30
Potential fire risks	Category A machinery spaces	A-60
	Accommodation spaces and high fire risk service spaces	A-30
	Low risk service spaces, machinery spaces other than category A machinery spaces, open decks	A-0
	Cargo spaces (other than ro-ro and vehicle spaces)	A-0
	Other ro-ro or vehicle spaces	A-30

For practical purposes, there is no fire integrity requirement around a weather deck intended to carry vehicles, only a steel bulkhead or deck is required between such an area and another enclosed space.

The Swedish Flag nevertheless clarifies that, on cargo ships, weather decks intended to carry vehicles are to be considered as cat (11) same as enclosed ro-ro or vehicle spaces, and therefore similarly insulated with respect to other spaces.

[Comments and interpretations by the Swedish Transport Agency regarding IMO Conventions, interpretation of SOLAS II-2/9.2.3.3.2.2 (11)]

It is to be noted that the fire integrity requirements for ro-ro and vehicle spaces have been reinforced by MSC.338(91) amending SOLAS requirements for ships constructed after 01/07/2014. Prior to this date:

- There was no firm fire integrity requirement between two ro-ro or vehicle spaces, only this footnote "*Bulkheads and decks separating ro-ro spaces shall be capable of being closed reasonably gastight and such divisions shall have "A" class integrity in so far as reasonable and practicable, if in the opinion of the Administration it has little or no fire risk.*"
- There was no fire integrity requirement between an open deck and a ro-ro or vehicle space, a mere steel bulkhead or deck was acceptable

4.3.4 Fire integrity

Fire integrity as per SOLAS corresponds to fire testing standards defined in IMO FTP Code. Dedicated fire test procedures are available for:

- Decks and bulkheads
- Pipe, duct, and electrical cable penetrations
- Doors and windows
- Fire dampers

A-60 is the highest fire resistance rating defined in SOLAS. It corresponds to a 60-minute-long fire test with 945°C maximum fire temperature.

SOLAS II-2/3 provides the following definition:

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

.1 they are constructed of steel or other equivalent material;

.2 they are suitably stiffened;

.3 they are insulated with approved non-combustible materials such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C above the original temperature, within the time listed below:

class "A-60"	*60 min*
class "A-30"	*30 min*
class "A-15"	*15 min*
class "A-0"	*0 min*

.4 they are constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test; and

.5 the Administration has required a test of a prototype bulkhead or deck in accordance with the Fire Test Procedures Code to ensure that it meets the above requirements for integrity and temperature rise.

[SOLAS II-2/3]

4.3.5 Ventilation

The above-mentioned fire integrity requirements are complemented by ventilation requirements which ensure that:

- The ventilation systems serving ro-ro and vehicle spaces are fully independent from those serving other spaces

[SOLAS II-2/9.7.2.1]

- The ventilation ducts serving ro-ro and vehicle spaces are insulated to A-60 standard when passing through other spaces

[SOLAS II-2/9.7.2.2 and SOLAS II-2/20.31.4.2 as interpreted by MSC.1/Circ.1120]

- The ventilation ducts serving other spaces are insulated to A-60 standard when passing through ro-ro and vehicle spaces

[SOLAS II-2/9.7.2.3]

4.3.6 Openings

Open ro-ro spaces and vehicle spaces may have openings on the side shell–mainly to ensure natural ventilation–or at their ends, possibly leading to a weather deck also intended for the stowage of vehicles. SOLAS II-2/20 currently includes a rather general requirement, stating that "*Permanent openings in the side plating, the ends or deckhead of the space shall be so situated that a fire in the cargo space does not endanger stowage areas and embarkation stations for survival craft and accommodation spaces, service spaces and control stations in superstructures and deckhouses above the cargo spaces.*"

[SOLAS II-2/20.31.5]

MSC.1/Circ.1615 proposes to go beyond this rather vague requirement and completely ban open ro-ro spaces on passenger ships. It is to be noted however that MSC.1/Circ.1615 is a mere guideline, therefore applicable only on a voluntary basis, and targets only passenger ships.

[MSC.1/Circ.1615 §4.2]

5 Ship integration requirement definition

Main author of the chapter: Obrad Kuzmanovic, FLOW.

This chapter gathers the requirements for division and subdivisions of ro-ro spaces regarding the ship integration aspect.

Operational, design and production aspects are described in the following sections.

5.1 Requirements and restrictions due to the rules and regulations

This topic is covered in-depth in Chapter 4, but some of the most important explanations of the regulations is mentioned in this section also, due to the high importance on the design of the vessels.

The main vertical fire zoning (as required by SOLAS Ch. II-2/9.2), may not be practicable in vehicle spaces of passenger ships and, therefore, equivalent protection must be obtained in such spaces on the basis on horizontal zone concept and by provision of an efficient fixed fire-extinguishing system. As this concept may extend to a substantial or entire length of the ship, introduction of fire-classed subdivisions will prevent the longitudinal fire spread to the same extent. Specific requirements related to the fire detection and extinguishing system, ventilation system, lifesaving appliances and other are addressed with respect to:

- Type of cargo space
- Type of ship (ro-ro cargo ship, ro-pax ship, vehicle carrier)
- Cargo space arrangement: adjacent spaces to the cargo space (Classification of space with respect to fire hazard)
- Construction of cargo space boundaries: structural fire protection
- Requirements for cargo spaces intended for the carriage of dangerous goods

Moreover, ro-ro spaces are defined by cargo requirements (type of cargo, cargo capacity, cargo stowing, clear height, etc.), stability requirements (longitudinal and vertical subdivision, loading conditions, etc.), rules and regulations requirements (fire safety etc.). With respect to the arrangement, ro-ro spaces can be divided as follows:

- **Open ro-ro space**
  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.
- **Weather deck**
  Weather deck is a deck which is completely exposed to the weather from above and from at least two sides.
- **Closed ro-ro space**
  Closed ro-ro spaces are ro-ro spaces which are neither open ro-ro spaces nor weather decks.

Additionally, the separation of ro-ro spaces, according to SOLAS, Ch. II-2, Pt. G, Regulation 19 for Carriage of Dangerous Goods, shall be as follows:

3.10.1 Separation shall be provided between a closed ro-ro space and an adjacent open ro-ro space. The separation shall be such as to minimize the passage of dangerous vapours and liquids between such spaces. Alternatively, such separation need not be provided if the ro-ro space is considered to be a closed cargo space over its entire length and fully complies with the relevant special Rules and Regulation requirements.

3.10.2 In ships having ro-ro spaces, a separation shall be provided between a closed ro-ro space and the adjacent weather deck. The separation shall be such as to minimize the passage of dangerous vapours and liquids between such spaces. Alternatively, a separation need not be provided if the arrangements of the closed ro-ro spaces are in accordance with those required for the dangerous goods carried on adjacent weather decks.

The introduction of subdivisions can help to satisfy these requirements and can prevent longitudinal fire spread and resulting loss of control of the fire.

Ro-ro and vehicle spaces not capable of being sealed and special category spaces 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 such spaces. Such water spray systems shall have, among others, a sufficient number of drainage valves. When fixed pressure water-spraying 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 fire-fighting operations, the drainage system below bulkhead deck shall be sized to remove no less than 125% of the combined capacity of both fixed fire-fighting system and the required number of fire hose nozzles. 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. Means shall be provided to prevent blockage of drainage arrangements.

This SOLAS requirement must be considered when designing new subdivision systems, especially in case of water curtains or walls.

5.2 Requirements and restrictions regarding operational and design aspects

Ro-ro spaces in ro-ro cargo and ro-pax ships are usually arranged all along the vessel, without longitudinal or transversal subdivision and with as less as possible obstructions, such as pillars, casings or other ship structures and equipment, as the lanes shall be as unbroken as possible. These design requirements regarding ro-ro space arrangement present a challenge regarding successful prevention and suppression of fire and the introduction of fire-class subdivisions (water walls, fabric curtains, etc.) can substantially reduce that fire spread threat.

Subdivision devices should not intrude into the clear height/width profile of the cargo space in order to not interfere with the loading capacity or manoeuvre of vehicles. The required free height for cargo can be a limiting factor for the type of closure devices that are feasible. Examples of typical arrangements in ro-ro spaces are illustrated in Figure 1 and Figure 2, where the equipment (piping, cables, etc.) are “incorporated” in the deck/side structure.

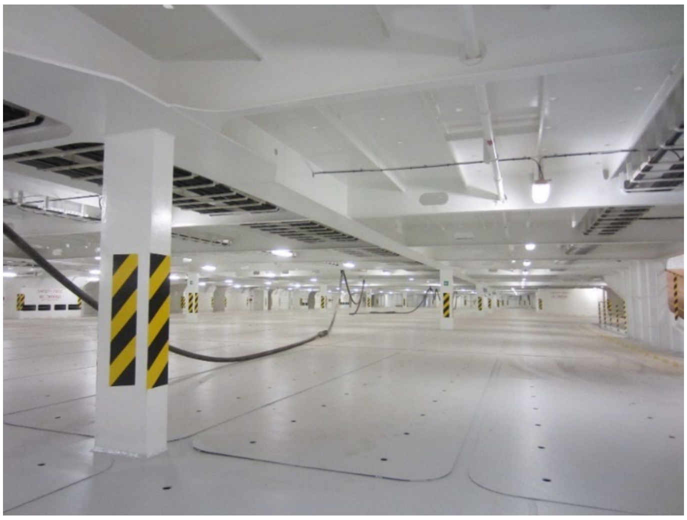

Figure 1. Typical ro-ro space (1)

Figure 2. Typical ro-ro space (2)

Design of a subdivision must be done with respect to some certain identified challenges:

- Coordination with the designs of all other equipment (hoistable car decks, movable ramp systems etc.) and systems piping and fittings in ship sides, casings or under deck, as seen in Figure 1 and Figure 2.
- Stowage patterns should be considered in general but are especially important for restricted areas, such as in lower holds, close to ramps, fore/aft ends of decks and at partial weather decks.
- Any division device fitted athwartships should be located along ship in such way to consider parking positions of trailers and trucks.
- Curtains or similar innovative equipment to be applied when cargo is located in way of closure may be investigated.
- Closing/opening operation should be such that cargo operations times are not prolonged. Solutions only to be engaged in case of fire may be evaluated.
- Annual costs associate with reduced cargo capacity will be very cost driving and therefore cargo separation should be avoided as far as practicable.
- Minimum fire division requirements A-0, A-30 etc. to be applied considering purpose of division. If division is only to prevent free flow of air/oxygen into for example an open aft closed ro-ro deck even solution not compliant with A-0 may be evaluated.

- Impact on fire patrolling and manual firefighting, by restricting passage and view, must be considered. Passage doors may have to be arranged in closure devices.

The new subdivision systems must not be hazardous to the crew and passengers and require additional means of escape beside the ones required. These systems should not have negative effect on ventilation requirements also and be simple from operational and maintenance aspects, if possible. In general, such systems should preferably not require any stricter regulation in comparison with the current rules. Closed circuit television (CCTV), detection, manual equipment location, drencher zones must be coordinated.

Furthermore, personnel safety must be properly considered. For example, a side folded wall could technically be possible but may need to be disregarded for safety and operational reasons since it poses an intrusion in the sidewalk, which poses a collision hazard. Except personnel safety, it may also delay cargo operations, cause loss of cargo and delay cargo handling.

Mitigation of risks with alternatively fuelled vehicles (AFV), especially regarding e-vehicles, is also becoming very important topic. In particular, the means of separation of dedicated areas for localization and charging of such vehicles should be taken into consideration. The appropriate level of insulation of such spaces could also be assessed.

Finally, the novel system for fire subdivisions must not use harmful materials and substances to the environment.

6 Water curtain as subdivision of ro-ro space

Main authors of the chapter: Rabah Mehaddi, Davood Zeinali and Pascal Boulet, LUL

This chapter is dedicated to water curtain and the work that has been conducted during the project. It includes description of the theory behind the efficiency of water curtain, performed model scale tests and identified challenges.

As a starting point, a theoretical study was conducted making use of academic knowledge on the ability of water curtains to block fire, heat, and smoke. This fundamental study was completed by a reduced scale study on a ro-ro space configuration which is also presented. This reduced scale study provided inputs for the design of water-based installations aimed at subdividing ro-ro spaces at large scale. These inputs were combined with the practical experience of such water curtains at real, considering potential application to ro-ro ships.

6.1 Basics of containment mechanisms

In the context of fire protection, the use of water is an essential tool, especially for its ability to extinguish a fire directly. There are two main types of systems that are currently used for fixed installations namely: sprinklers and water mist. In the case of a sprinkler, the spray is produced by the impact of a water jet with low pressure on a profile which allows to atomize it. In this case the size of the droplets is relatively large, usually more than 1mm. However, in the case of a water mist, it is produced by the injection of a water jet through a small orifice (5mm in this study) with a high pressure. Thus, a spray is produced with water droplets of less than 1mm. The atomization process is related to the intrinsic turbulence of the jet and the velocity gradient with the ambient air.

When activating a water spray within the frame to space subdivision, the expected effect on smoke propagation is to stop the smoke thanks to the momentum induced by the spray, with the down-drag effect induced by the droplets. While hindering smoke propagation, the area downstream the curtain should be protected from heat and soot transported by the combustion products. Simultaneously, a cooling effect is also expected, in particular due to droplet evaporation, which is favoured by the small size of the droplets currently injected by water mist systems. This should even help to contain the fire itself by cooling its surroundings, or the flames directly. Finally, droplets are well-known to interact with radiation emitted by the flame through absorption and scattering effect, which should also limit the heat propagation.

In the present case of a water curtain, several nozzles are aligned in such a way as to produce a "curtain" of water droplets, knowing that it will then be able to test several curtains of water one behind the other to reinforce the expected effects. The question to investigate is the possibility to compartmentalize a space thanks to these water curtains. How to make a water curtain as close as possible to the effect of a real “wall” from the point of view of the containment of smoke and heat transferred from the fire? How to enhance its capacity to scatter, reflect or absorb the radiation from the flame?

To answer these questions, separate discussion follows on the hydrodynamic effects of the spray related to smoke containment and the radiative shielding effect, as these two effects involved different physical mechanisms.

6.1.1 Hydrodynamic interaction of a spray with smoke

The interaction of a spray with hot smoke has been studied by many researchers [1-10]. The two main situations that have been considered are the interaction of the spray with a stagnant layer of smoke as in the case of a room in which a fire is taking place or the interaction with a moving layer of smoke as in tunnels or corridors. Bullen [1] evaluated the drag experienced by the water droplets and compared it to the buoyancy of the stagnant smoke layer. This comparison allows the authors to clarify whether or not the smoke layer is de-stratified or not by the spray (meaning that a mixing occurs between the smoke layer initially flowing in the upper part of the considered space and the smoke-free layer in the bottom part). Cooper [2] considered a compartment fire problem with a two-layer representation of the smoke stratification (hot smoke at the top and cold fresh air in the bottom). In this context, this author considered a more complex problem involving six possible flow conditions for possible interaction between the smoke layer and water droplets. Chow and Yao [3] developed a mono-dimensional model based on heat and mass balance for the smoke layer. Li et al [4] also developed similar mathematical models where they evaluated the stability of the smoke layer. Later Li and Spearpoint [6] developed a simplified hand calculation equation which might be applied in practical way by fire engineers in order to evaluate the down drag effect due to the spray.

In the case where the smoke layer is in movement, the problem becomes more complex because of an interaction between the top stream of hot smoke and the lower stream of fresh air. Because of these various additional complexities, there is still much controversy about the use of sprinklers and water mist in tunnels [7-8]. Ingason [11] and Li and Ingason [12] studied in a small-scale model the effect of the water spray on a fire inside a tunnel where a heavy goods vehicle (HGV) fire source was simulated by a wood-crib. The study has been subsequently extended to the large-scale problem by Ingason et al. [13] where a focus has been devoted to the effect of the water sprays on fire heat released rate. Blanchard et al. [14] studied the effect of the sprinklers on the smoke cooling and de-stratification using mid-scale experiments and CFD simulations. Sun et al. [15] and Li et al [16] considered the effects of a water curtain on a smoke layer in a small-scale experimental setup. By evaluating the temperature fields, they argued that the spray is effective in blocking the smoke flow. Note that however, their system incorporates the effects of ventilation, and the tunnel was opened at both sides. Later Liu et al. [18] evaluated the combined effect of a water mist system and longitudinal ventilation on the fire and smoke dynamics. Mehaddi et al. [19] and Yang et al. [20] studied the possibility of blocking smoke in a tunnel under construction, based on experiments at small scale and simulations. They observed that heat and smoke toxicity were largely reduced by the presence of the water curtain, however, the system fails in blocking completely the smoke as can do a real wall. Furthermore, even if beneficial effects of the water curtain have been observed, there are still those adverse effects related to the de-stratification of smoke and the accumulation of more toxic smoke on the other side of the wall. Moreover, the fire is not completely flooded, smouldering at least is observed and in some cases, a coupling between the natural ventilation of the fire and the turbulent mixing induced by the spray allows the fire to flicker in a cyclic but effective way.

We should mention at this point that the case of a ro-ro ship is in between the two limiting cases that have been described. Indeed, due to the corridor-like geometry of the ro-ro spaces, the smoke flow is longitudinal at a certain distance from the fire source. However, as the width of the deck is much larger than the typical width of a tunnel or a corridor, the smoke flow velocity is relatively slow. This situation needs to be specifically studied.

Moreover, in all the above-referenced studies, the smoke is disturbed by the droplets that moves with a high velocity. In that case, there is a transfer of momentum from the droplets to the gas phase due to the drag. A second important mechanism is the smoke cooling due the heat transfer between the droplets and hot smoke which results in the evaporation of the droplets. As droplets crosses a large range of sizes, the drag and heat transfer might depend on their specific Reynolds number and Peclet numbers. For instance, the drag coefficient is known to be mainly a function of the Reynolds number. The Nusselt number which measures the amplitude of heat transfer is also mainly a function of the Peclet number. These numbers critically depend on droplets size. Thus it is easy to see that the rate of evaporation of the water droplets is greatly enhanced when using “water mist” as compared to “sprinklers”. However, the drag effect of the spray induced by the friction of droplets with the smoke is also increased, which results in a greater de-stratification of the smoke.

Furthermore, an important effect is the oxygen depletion and oxygen dilution with water vapour. The mechanism consists in the fact that the water vapour expansion can disturb the flame oxygenation. However, this effect happens if the vaporization happens close or on the fire. On larger scale, the water vapour expansion inside the compartment can significantly reduce the oxygen concentration inside the compartment.

Finally, if the spray contains large droplets that are not likely to evaporate, then they fall to the ground and bounce off in a splash that explodes the drop into a myriad of smaller drops. These small drops can be carried to the fire by the fresh air stream driven by the fire. These small drops can then directly cool the flame, reducing its size. In this case the effect can be described as rather beneficial. However, in other cases, the agitation effects induced by the spray increase the turbulence in the air stream inside the compartment. In this case, the effect will be rather negative as it will fan the fire and increase its heat released rate. This effect is generally refereed as Kinetic effect.

6.1.2 Radiative shielding

Radiative shielding effect is related to the absorption and scattering ability of droplets, which decreases the radiative heat flux transmitted through the spray. Readers are referred to Mehaddi et al. [19] (among other studies dedicated to spray – radiation interactions) for further details. This publication reminds that the use of water sprays as radiative shields has received a lot of attention in the past decades. It is now well known that droplets absorb, and scatter radiation emitted from the fire, with an efficiency governed by the droplet size, water concentration and water curtain thickness. By using the right water injection conditions there is no doubt that high attenuation efficiency can be reached and that theoretically an attenuation up to 100% can be achieved. Knowing these injection characteristics from measurements or simulation allows predicting the radiation attenuation using numerical simulations.

What is called here a radiative shielding effect can be evaluated through the attenuation, i.e. the ratio between incident radiative flux and transmitted flux through the curtain. It was studied experimentally using heat flux gauges and infrared cameras, as explained in the next subsection.

6.2 Reduced scale experimental evaluation of water curtains

A model setup of the cargo deck of a ro-ro ship with a scale of 1 to 12.5 has been used to evaluate the containment of fire using water mist curtains. As shown in Figure 3, the setup consists of a corridorlike compartment measuring 8 m x 2 m x 0.4 m with water curtains made up of one or two rows of water mist nozzles operating at pressures ranging from 3 to 8 bar. Two series of tests are considered: the first series is aimed at evaluating the radiative shielding effect of water mist curtains, while the second series is aimed at assessing the smoke shielding capability of these curtains.

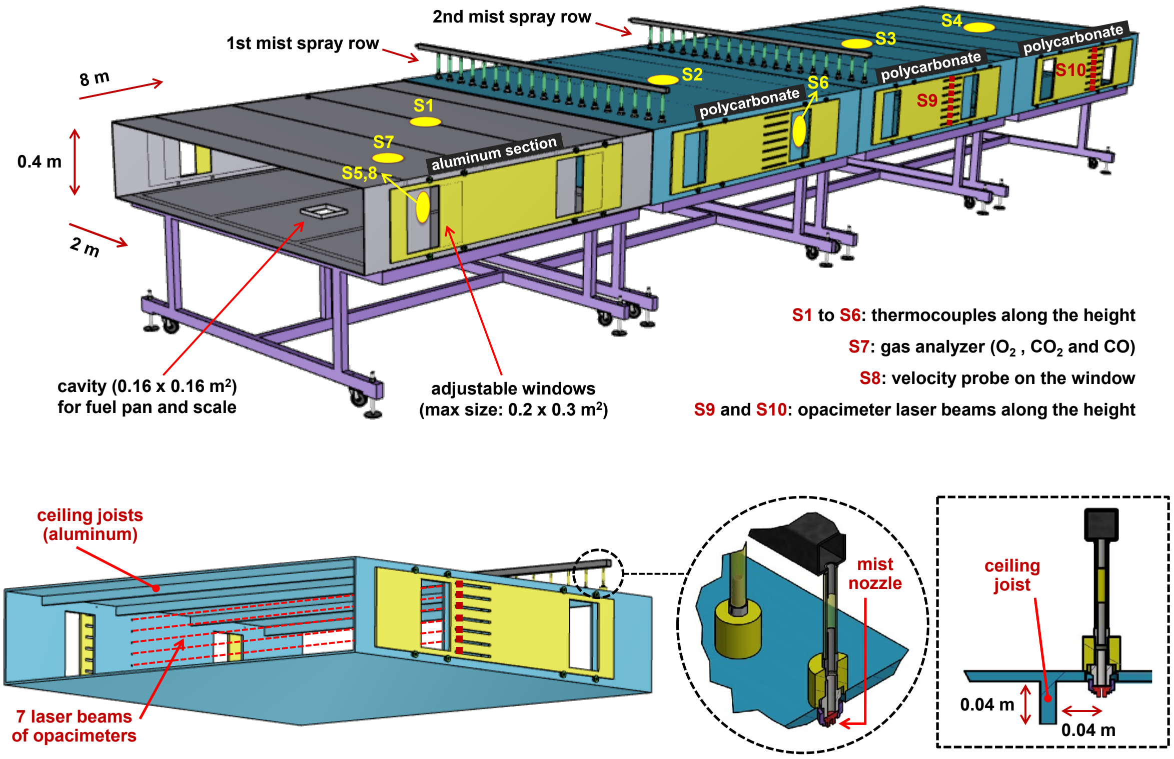

Figure 3. Set-up of the reduced scale experiments, consisting of one aluminium section for the fire zone, and 3 transparent polycarbonate sections, each measuring 2 m long. Note: an aluminium lid is used to close the side of the deck near the fire in most tests (see Table 4 for the fire scenarios) but this is not shown to allow visualizing the interior.

See Table 4 for the scaling with respect to real cargo deck dimensions.

Table 4. Scaling of the experimental setup with respect to the cargo compartment of a ro-ro ship

Feature	Model	Ship	Scaling factor*
Deck length	8 m	100 m	$\alpha = 12.5$
Deck width	2 m	25 m	α
Deck height	0.4 m	5 m	α
Fire Heat Release Rate (HRR)	3–30 kW	2–17 MW	$\alpha^{5/2}$
Flowrate of each nozzle	0.2–0.4 L/min	55–220 l/min	$\alpha^{5/2}$
Mean diameter of water droplets	130-170 µm	350-600 µm	$\alpha^{1/2}$
Duration of fire	300 s	1060 s	$\alpha^{1/2}$
* The scaling is based on the correlations reported by Yu [21].			

6.2.1 Experiments with a black body

In the first series of conducted experiments, the radiation source is an electric black body with a fixed temperature of 550°C placed in the fire section with a distance of 1 m from the first water curtain as shown in Figure 4. In these tests, the aluminium section is not used due to the size of the black body.

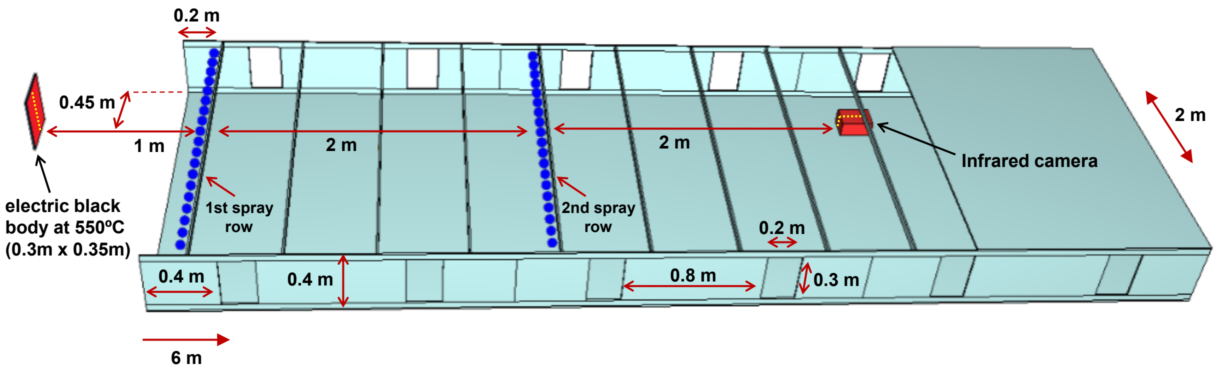

Figure 4. Set-up of the experiments with a black body. The ceiling is shown partially in order to allow visualizing the interior

To quantify the level of radiation containment by the water curtains, an infrared camera is used. Correspondingly, the radiation levels measured without and with water curtain(s) are compared to calculate the containment efficiency in terms of radiative attenuation values. Moreover, the experiments have been repeated a few times to verify the repeatability of the observations.

To evaluate the impact of the number of water curtains and their position on the level of radiation containment, the two rows of water curtains are placed at different distances from the radiation source and are used one at a time or both at the same time. Moreover, to examine the influence of water flowrate and pressure, experiments are conducted at flowrates ranging from 0.2 to 0.4 L/min/nozzle, corresponding to a water pressure range from 3 to 8 bar. The conducted experiments are listed in Table 5.

Table 5. Experiments conducted with a black body to evaluate the radiative shielding of water mist curtains

Test no.	**Water pressure (bar)**	**Flowrate (L/min/nozzle)**	**Row of water curtain used****
1	3	0.2	1st
2-1*	3	0.2	2nd
2-2*	3	0.2	2nd
3	3	0.2	Both
4-1*	5	0.3	1st
4-2*	5	0.3	1st
5	5	0.3	2nd
6	5	0.3	Both
7-1*	8	0.4	1st
7-2*	8	0.4	1st
8	8	0.4	2nd
9	8	0.4	Both
* Repeated test ** The 1st and 2nd rows of water spray curtains are fixed as shown in			

The experiments conducted with a black body suggest that the position of the curtain does not have a significant impact on the radiative shielding capability of the water curtains with a pressure of 5 bar or above. Secondly, higher radiative attenuation levels are achieved at higher water flowrates and water pressures (by over 50%). Moreover, the attenuation level increases with the number of water curtains, with the highest attenuation achieved being 80% for 2 water curtains operating at a pressure of 8 bar.

Accordingly, higher attenuation levels are expected to be possible if higher water flowrates and pressures are applied. This is while the number of water curtains seems to be less influential for radiative attenuation than the water flowrate and pressure. Correspondingly, 1 curtain with a high flowrate provides a higher radiative shielding compared to 2 curtains with an identical total flowrate. Lastly, the experiments suggest that the water mist curtains with mean droplet size bigger than 130 µm (in terms of mean Sauter diameter) offer a radiative shielding capability which does not change strongly with the radiation wavelength (in the range of 1.5 to 5 µm).

6.2.2 Experiments with a pool fire

In the second series of experiments, the water mist curtains are tested for containment of smoke and heat generated by a heptane or diesel pool fire with a power ranging from 3 to 30 kW. Furthermore, experiments with wood cribs as well as wooden cargo items have been conducted. The study targets of these experiments are summarized in Table 6, and the conducted tests are listed in Table 7.

Table 6. Target study parameters in the pool fire experiments

Parameter	Option 1	Option 2	Option 3
Fire location*	End of corridor	Centre of corridor	--
Fire size	5–30 kW (≈ 17 MW truck fire)	2–8 kW (≈ 4 MW car fire)	3–12 kW (≈ 7 MW car fire)
Fuel	Heptane (0.15 m diameter pool)	Diesel (0.13-0.15 m diameter pool)	Wood cribs
Corridor ends	Closed only on the fire side	Closed on both ends	Open on both ends
Area of windows	15% of side area (open deck**)	5% of side area (closed deck**)	0% of side area (closed deck**)
Cargo load in the deck	None	Full (inert boxes ≈ vehicles)	(inert + wood boxes ≈ vehicles)
Curtain row	1st	2nd	Both
Distance of curtains	2 m	2.4 m	0.4 m
Curtain configuration	Series	Straddle	--
Flowrate per nozzle	0.4 L/min (≈ 8 bar pressure)	0.3 L/min (≈ 5 bar pressure)	0.2 L/min (≈ 3 bar pressure)

* See caption of Table 4 for the description of the fire scenarios.

** Based on the maritime standards of SOLAS II-2/3, a cargo deck with opening areas more than 10% of the total side area can be considered to be an 'open deck', while that with smaller opening areas constitutes a 'closed deck'. Note that the deck may or may not be open at one or both ends.

Table 7. Experiments conducted to assess the effectiveness of water curtains for containment of smoke and heat of a pool fire in the reduced scale deck setup. The highlights indicate the changes made with respect to the first test.

Test no.	Fuel	Fire size	Fire scenario	Area of openings	Curtain[a]	Flow rate per nozzle	Distance of curtains	Curtain configuration	Cargo load
1-1[b]	Diesel	2–8 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
1-2[b]	Diesel	2–8 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
1-3[b]	Diesel	2–8 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
2	Diesel	2–8 kW	E1[c]	15%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None
3	Diesel	3–12 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
4	Diesel	2–8 kW	E1[c]	0%	1st water curtain	0.3 L/min	--	--	None
5	Diesel	2–8 kW	E1[c]	0%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None

6	Diesel	2–8 kW	E1[c]	0%	No curtain	--	--	--	None
7	Diesel	3–12 kW	E1[c]	0%	No curtain	--	--	--	None
8	Diesel	3–12 kW	E1[c]	15%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None
9	Diesel	3–12 kW	E1[c]	15%	No curtain	--	--	--	None
10	Diesel	2–8 kW	E1[c]	15%	No curtain	--	--	--	None
11-1[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	None
11-2[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	None
12-1[b]	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
12-2[b]	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
12-3[b]	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.3 L/min	--	--	None
13	Heptane	5–30 kW	E1[c]	15%	2nd water curtain	0.3 L/min	--	--	None
14	Heptane	5–30 kW	E1[c]	15%	2nd water curtain	0.4 L/min	--	--	None
15	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.4 L/min	--	--	None
16	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.4 L/min	2 m	Series	None
17	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None
18	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.2 L/min	2 m	Series	None
19	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.2 L/min	--	--	None
20	Heptane	5–30 kW	E1[c]	15%	2nd water curtain	0.2 L/min	--	--	None
21	Heptane	5–30 kW	E1[c]	0%	2nd water curtain	0.2 L/min	--	--	None
22	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.35 L/min	--	--	None
23	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.2 L/min	2 m	Series	None
24	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.2 L/min	--	--	None
25	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None
26	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.3 L/min	--	--	None
27-1[b]	Heptane	5–30 kW	E1[c]	0%	2nd water curtain	0.3 L/min	--	--	None
27-2[b]	Heptane	5–30 kW	E1[c]	0%	2nd water curtain	0.3 L/min	--	--	None
28	Heptane	5–30 kW	E1[c]	0%	2nd water curtain	0.4 L/min	--	--	None
29	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.4 L/min	--	--	None
30	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.4 L/min	2 m	Series	None
31	Heptane	5–30 kW	E1[c]	5%	1st water curtain	0.4 L/min	--	--	None
32	Heptane	5–30 kW	E1[c]	5%	1st water curtain	0.3 L/min	--	--	None
33	Heptane	5–30 kW	E1[c]	5%	1st water curtain	0.2 L/min	--	--	None
34	Heptane	5–30 kW	E1[c]	5%	1st and 2nd water curtains	0.2 L/min	2 m	Series	None
35	Heptane	5–30 kW	E1[c]	5%	1st and 2nd water curtains	0.3 L/min	2 m	Series	None
36	Heptane	5–30 kW	E1[c]	5%	1st and 2nd water curtains	0.4 L/min	2 m	Series	None
37	Heptane	5–30 kW	E1[c]	5%	No curtain	--	--	--	None
38	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.4 L/min	0.4 m	Series	None
39	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.3 L/min	0.4 m	Series	None
40	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.2 L/min	0.4 m	Series	None
41	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.4 L/min	0.4 m	Series	None
42	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.3 L/min	0.4 m	Series	None
43	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.2 L/min	0.4 m	Series	None
44	Heptane	5–30 kW	C1[c]	0%	No curtain	--	--	--	None
45-1[b]	Heptane	5–30 kW	C1[c]	0%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
45-2[b]	Heptane	5–30 kW	C1[c]	0%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
46	Heptane	5–30 kW	C1[c]	15%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
47	Heptane	5–30 kW	C1[c]	15%	No curtain	--	--	Straddle[d]	None
48-1[b]	Heptane	5–30 kW	C1[c]	0%	1st and 2nd water curtains	0.3 L/min	2.4 m	Straddle[d]	None
48-2[b]	Heptane	5–30 kW	C1[c]	0%	1st and 2nd water curtains	0.3 L/min	2.4 m	Straddle[d]	None
49	Heptane	5–30 kW	C1[c]	15%	1st and 2nd water curtains	0.3 L/min	2.4 m	Straddle[d]	None
50	Heptane	5–30 kW	C1[c]	15%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
51	Heptane	5–30 kW	C1[c]	15%	1st and 2nd water curtains	0.2 L/min	2.4 m	Straddle[d]	None
52	Heptane	5–30 kW	C1[c]	0%	1st and 2nd water curtains	0.2 L/min	2.4 m	Straddle[d]	None
53	Diesel	3–12 kW	C1[c]	0%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
54	Heptane	5–30 kW	C0[c]	0%	No curtain	--	--	--	None
55	Heptane	5–30 kW	C0[c]	15%	No curtain	--	--	--	None
56	Heptane	5–30 kW	C0[c]	15%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
57	Heptane	5–30 kW	C0[c]	0%	1st and 2nd water curtains	0.4 L/min	2.4 m	Straddle[d]	None
58	Heptane	5–30 kW	C0[c]	0%	1st and 2nd water curtains	0.2 L/min	2.4 m	Straddle[d]	None
59	Heptane	5–30 kW	C0[c]	15%	1st and 2nd water curtains	0.2 L/min	2.4 m	Straddle[d]	None
73-1[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	Full[g]

73-2[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	Full[g]
73-3[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	Full[g]
73-4[b]	Heptane	5–30 kW	E1[c]	15%	No curtain	--	--	--	Full[g]
74	Heptane	5–30 kW	E1[c]	0%	No curtain	--	--	--	Full[g]
77	Heptane	5–30 kW	E1[c]	15%	1 water curtain	0.3 L/min	--	--	Full[g]
78	Heptane	5–30 kW	E1[c]	0%	1 water curtain	0.3 L/min	--	--	Full[g]
79	Heptane	5–30 kW	E1[c]	0%	1st and 2nd water curtains	0.3 L/min	2 m	Series	Full[g]
80	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.4 L/min	--	--	Full[g]
81	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.4 L/min	--	--	Full[g]
82	Heptane	5–30 kW	E1[c]	15%	1st water curtain	0.2 L/min	--	--	Full[g]
83	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.2 L/min	--	--	Full[g]
86	Heptane	5–30 kW	E1[c]	15%	1st and 2nd water curtains	0.4 L/min	2 m	Series	Full[g]
88	Heptane	5–30 kW	E0[c]	15%	No curtain	--	--	--	Full[g]
96	Heptane	5–30 kW	E2[c]	15%	No curtain	--	--	--	Full[g]
97	Heptane	5–30 kW	E2[c]	0%	No curtain	--	--	--	Full[g]
100-1[b]	Heptane	5–30 kW	E2[c]	15%	1st and 2nd water curtains	0.2 L/min	2 m	Series	Full[g]
100-2[b]	Heptane	5–30 kW	E2[c]	15%	1st and 2nd water curtains	0.2 L/min	2 m	Series	Full[g]
101	Heptane	5–30 kW	E2[c]	15%	1st and 2nd water curtains	0.4 L/min	2 m	Series	Full[g]
102	Heptane	5–30 kW	E2[c]	0%	1st water curtain	0.4 L/min	--	--	Full[g]
103	Heptane	5–30 kW	E2[c]	0%	2nd water curtain	0.4 L/min	--	--	Full[g]
104	Heptane	5–30 kW	E2[c]	0%	1st and 2nd water curtains	0.2 L/min	2 m	Series	Full[g]
105	Heptane	5–30 kW	E2[c]	0%	1st and 2nd water curtains	0.4 L/min	2 m	Series	Full[g]
106	Heptane	5–30 kW	E2[c]	15/2% [h]	1st and 2nd water curtains	0.4 L/min	2 m	Series	Full[g]
107	Heptane	5–30 kW	E2[c]	15%	1st and 2nd fabric curtains	--	2 m	car height[e]	Full[g]
108	Heptane	5–30 kW	E2[c]	0%	1st fabric + water curtain[i]	0.2 L/min	--	full height[e]	Full[g]
109-1[b,j]	Heptane	5–30 kW	E2[c]	0%	1st fabric + water curtain[i]	0.4 L/min	--	full height[e]	Full[g]
109-2[b,j]	Heptane	5–30 kW	E2[c]	0%	1st fabric + water curtain[i]	0.4 L/min	--	full height[e]	Full[g]
110	Heptane	5–30 kW	E2[c]	0%	1st fabric + water curtain[i]	0.4 L/min	--	car height[e]	Full[g]
111	Heptane	5–30 kW	E1[c]	0%	1st fabric + water curtain[i]	0.4 L/min	--	full height[e]	Full[g]
112	Heptane	5–30 kW	E1[c]	15%	1st fabric + water curtain[i]	0.4 L/min	--	full height[e]	Full[g]
113[k]	Heptane	5–30 kW	E1[c]	0%	1st fabric + water curtain[i], 2nd fabric curtain	0.4 L/min	2 m	full height[e]	Full[g]
114	Heptane	5–30 kW	E2[c]	0%	2nd fabric + water curtain[i]	0.4 L/min	--	full height[e]	Full[g]
115	Wood1[l]	3–18 kW	E1[c]	15%	No curtain	--	--	--	Full[g]
116	Wood1[l]	3–18 kW	E1[c]	15%	1st water curtain	0.4 L/min	--	--	Full[g]
117	Wood2[m]	3–9 kW	E1[c]	15%	No curtain	--	--	--	Full[g]
118	Wood2[m]	3–9 kW	E1[c]	15%	1st water curtain	0.4 L/min	--	--	Full[g]
119[n]	Wood3[n]	5–60 kW	E1[c]	15 -> 0%[n]	1st water curtain then 1st fabric + water[n]	0.4 L/min	--	full height[e]	Full[g]
120-1[b,o]	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.4 L/min	--	--	Full[g]
120-2[b,o]	Heptane	5–30 kW	E1[c]	0%	1st water curtain	0.4 L/min	--	--	Full[g]
121[o]	Heptane	5–30 kW	E1[c]	0%	1st fabric + water curtain[i]	0.4 L/min	--	truck height[e]	Full[g]
a	The 1st and 2nd curtain row are fixed at the locations in Figure 3								
b	Repeated test.								
c	The fire scenario abbreviations indicate, firstly, the location of the fire: 'E' = end of corridor, and 'C' = centre of corridor; and secondly, the presence of walls that close the corridor from either end: '0' = no walls on either end of the corridor, '1' = one wall closing the corridor on the fire side, '2' = two walls closing the corridor from both ends.								
d	In the 'straddle' configuration, the fire section is the second section along the corridor, such that two water curtains can straddle the fire and contain it from both sides with a distance of 2.4 m from one another.								
e	The full height fabric curtain covers the entire cross-section of the corridor (0.4 m high), while the car height curtain covers only the top 0.26 m, considering that the curtains may drop on cars in reality. In addition, the truck height covers only the top 0.15 m.								
f	In test 63, the curtain was present since t = 0 s.								
g	Cargo arrangement is as shown in Figure 5.								
h	In test 106, the windows were fully open on one side of the deck while they were fully closed on the other side.								
i	When the fabric and water curtains are used together, the fabric curtain is allowed to drop down before activating the water curtain. This is to make sure that the smoked mixed by the water spray is trapped in front of the fabric curtain.								
j	In tests 109-1 and 109-2, the fire self-extinguished at t = 285 s and t = 244 s, respectively.								
k	In test 113, the fire self-extinguished at t = 238 s.								
l	Wood1 signifies wood cribs made with the surface area of 0.2 x 0.2 m^2 and a height of 0.088 m, placed on top of a pool containing 10 g heptane for an initially uniform and repeatable ignition pattern.								

m	Wood2 signifies wood cribs made with the surface area of 0.2 x 0.2 m^2 and a height of 0.14 m, placed on top of a pool containing 10 g heptane for an initially uniform and repeatable ignition pattern.
n	In test 119, the 5-30 kW heptane pool fire was surrounded by wooden boxes serving as combustible cargo items. The 1st water curtain was activated at *t* = 180 s as usual, and the windows were open since the beginning of the test. However, at *t* = 270 s, the windows were closed, and the 1st fabric curtain was activated (full height), while the 1st water curtain remained active too. Subsequently, the fire self-extinguished at *t* = 317 s.
o	In tests 120-1, 120-2 and 121, the cargo items were placed beneath the curtain to assess the curtain's functionality with cargo obstruction.

In each experiment, the fire is allowed to burn freely for 3 minutes, after which the curtains are activated and kept in place for 2 minutes. The containment effects are then evaluated through the measurements of incident radiation, opacity, and gas temperatures at various locations along the height and length of the deck and the windows, but also through the measurements of gas velocities from the window opposite the fire. In addition, the mass of the pool is recorded using a scale to estimate the heat release rate from the fire, and the concentrations of O_2 and CO are monitored near the fire using a gas analyser to monitor the efficiency of combustion. The arrangement of cargo in the tests are illustrated in Figure 5.

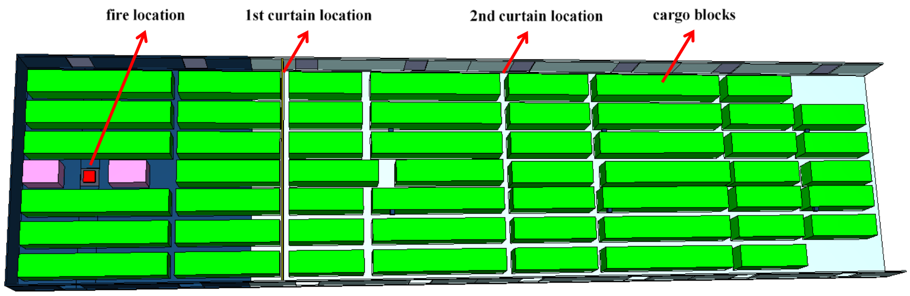

Figure 5. The arrangement of cargo in tests with a fully loaded deck. Near the fire, autoclaved cellular concrete blocks are used, while further away expanded polystyrene blocks are used, representing trailers and vehicles.

The soot volume fraction averaged over height provides a very good measure of the amount of (particulate) smoke going through the cross-section of the corridor. The average soot volume fraction can be obtained using the data of the opacimeter laser beams installed at every 0.05 m height. Based on the work of Krishnan et al. [22]:

$$f_v = -\lambda \cdot \ln(I_L / I_0) / (L \cdot K_e) \tag{1}$$

where f_v is the soot volume fraction, λ is the wavelength of the laser beam (i.e., 640 nm), I_L is the remaining intensity of light after traveling through smoke for distance L (i.e., the corridor's width which is 2 m), I_0 is the initial intensity of the laser beam, and K_e is the dimensionless extinction coefficient which has an average value of 8.4 and is relatively independent of fuel type and wavelength [22]. An example evolution profile of f_v obtained using Eq. (1) is shown in Figure 6 for a corridor-end fire (scenario 'E1') with open windows and no cargo, facing a single water curtain at the location of the 2nd spray row with a pressure of 8 bar.

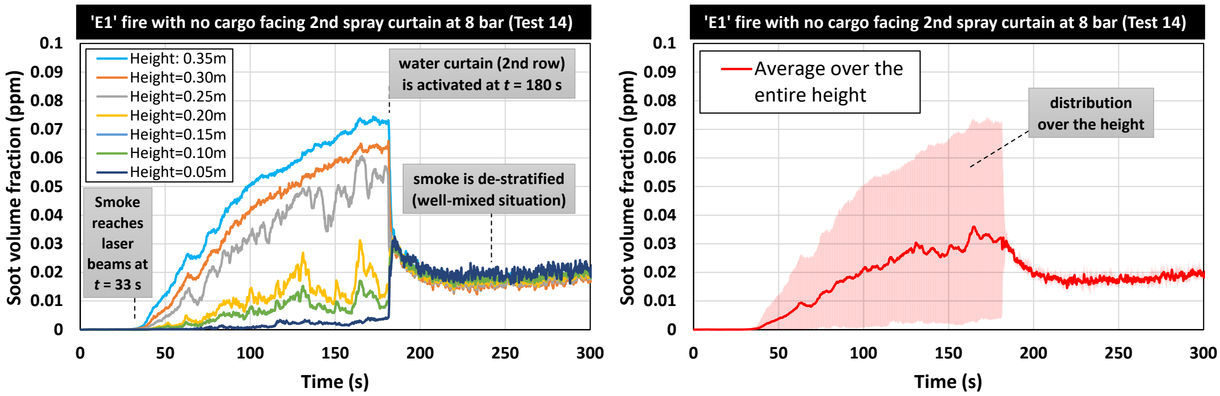

Figure 6. Temporal profiles of soot volume fraction (i.e., f_v in Eq. (1)) across the height of the deck in test 14 (with open windows and no cargo) based on data obtained using laser row 'S9'. The water curtain has a pressure of 8 bar and is placed at the location of the 2nd spray row. On the graph shown to the right, the shading indicates the distribution of soot volume fraction levels across the height at position S9. For positions, see Figure 3.

As Figure 6 indicates, the activation of a water curtain causes the smoke to de-stratify. In cases where there is no cargo present in the deck, this creates a perfectly mixed environment inside the deck, while the amount of smoke going through the corridor stabilizes (see t = 200 s), although this is only the case when the curtain is further away from the fire (i.e., at the location of the second spray row).

If the water curtain is located closer to the fire, the HRR of the fire increases significantly once the water curtain is activated, see Figure 7. In this case, the amount of smoke going through the curtain is initially decreased, while later the increase in the HRR causes the amount of smoke to increase again, surpassing that of the case with no water curtain (see t = 250 s). Note that the increase in the HRR is due to the turbulent mixing and rapid pulling of air into the deck through the windows caused by the water curtain's high-velocity spray. The turbulence disturbs the natural plume of the fire and allows for better mixing of air and fuel for combustion, thereby increasing the HRR. This is a 'kinetic effect' [23] which is most significant when the curtain operates at a high pressure.

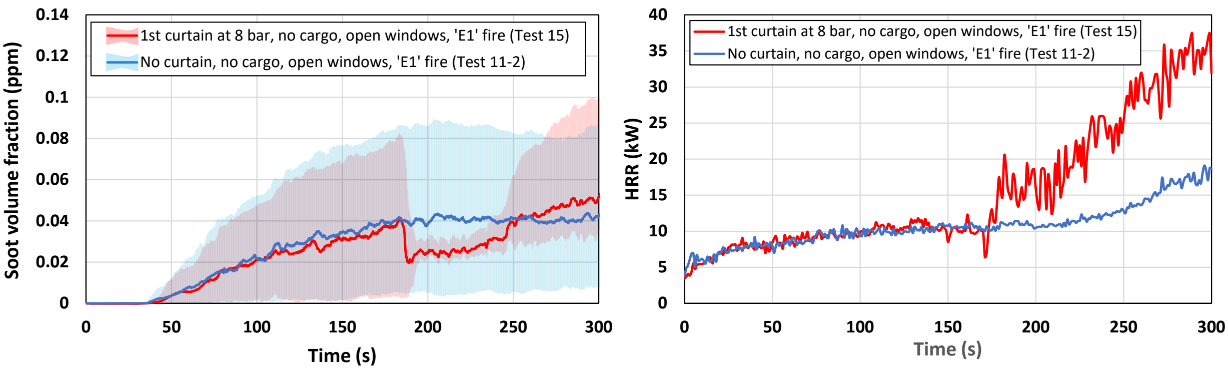

Figure 7. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests with and without water curtain containment (with open windows and no cargo). The water curtain has a pressure of 8 bar and is placed at the location of the 1st spray row. On the graph shown to the left, the average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9'. For positions, see Figure 3.

In the presence of cargo in the deck, the kinetic effect of a high-pressure curtain is less pronounced as the fire is shielded behind the cargo. Nevertheless, the HRR is still noticeably increased, see Figure 8. Consequently, when a high-pressure curtain is used near the fire in the presence of cargo, the amount of smoke going through the corridor eventually increases beyond that observed with no curtain (see the soot volume fraction values after *t* = 250 s).

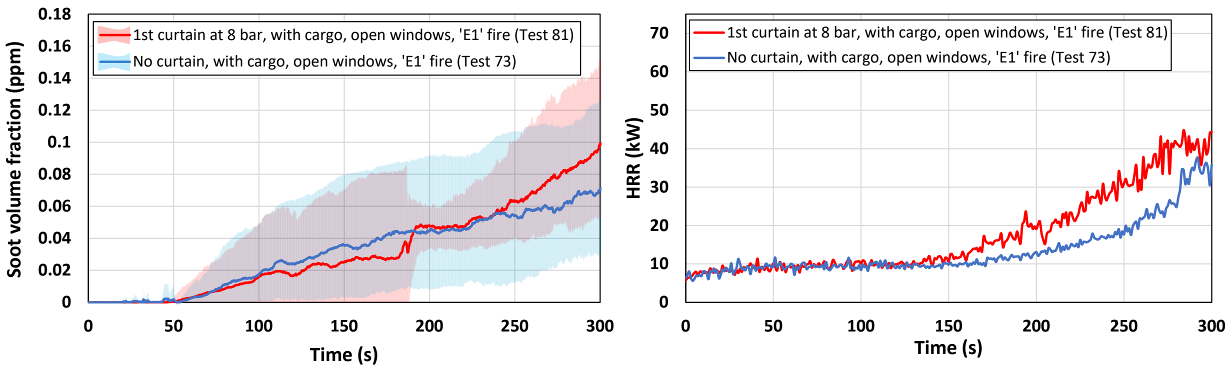

Figure 8. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests with and without water curtain containment (with cargo and open windows). The water curtain has a pressure of 8 bar and is placed at the location of the 1st spray row. On the graph shown to the left, the average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9'. For positions, see Figure 3.

When the windows are closed, the high-pressure curtain initially increases the HRR, but the fire quickly runs out of oxygen, so it starts to exhibit an oscillatory (i.e., cyclical) behaviour: the HRR goes down and more oxygen becomes available, allowing the HRR to increase again, thereby reducing the oxygen levels again, so on and so forth. This in turn causes the level of smoke production to stabilize, such that there is less smoke going through the corridor compared to when no curtain is used (see the soot volume fraction values in Figure 9 after *t* = 275 s). This indicates that the water wall solution is most effective when the windows are closed, i.e., in a 'closed-deck' configuration.

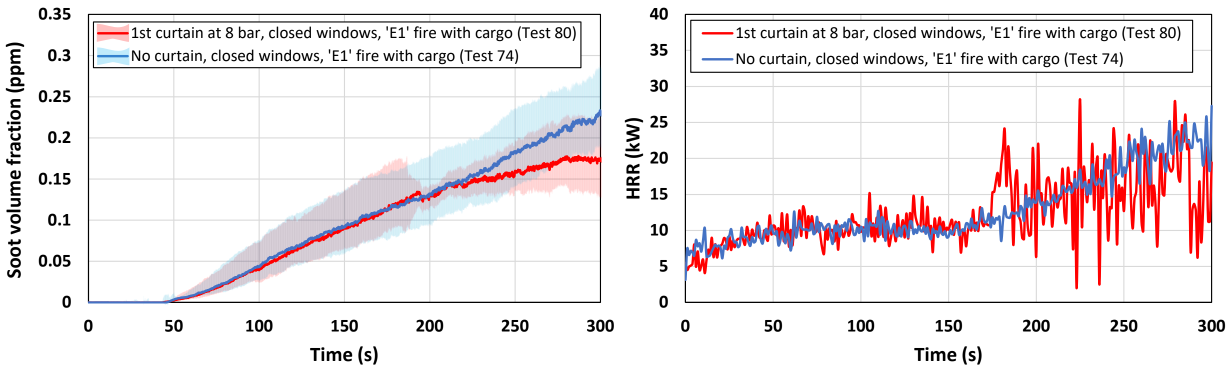

Figure 9. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests with and without water curtain containment (with cargo and closed windows). The water curtain has a pressure of 8 bar and is placed at the location of the 1st spray row. On the graph shown to the left, the average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9'). For positions, see Figure 3.

The distance between the curtains does not seem to have a strong impact on the smoke containment capability of the curtains. More specifically, two curtains separated by a distance of either 0.4 m or 2 m show nearly identical levels of smoke passing though the curtains, regardless of the water flowrate level, see Figure 10.

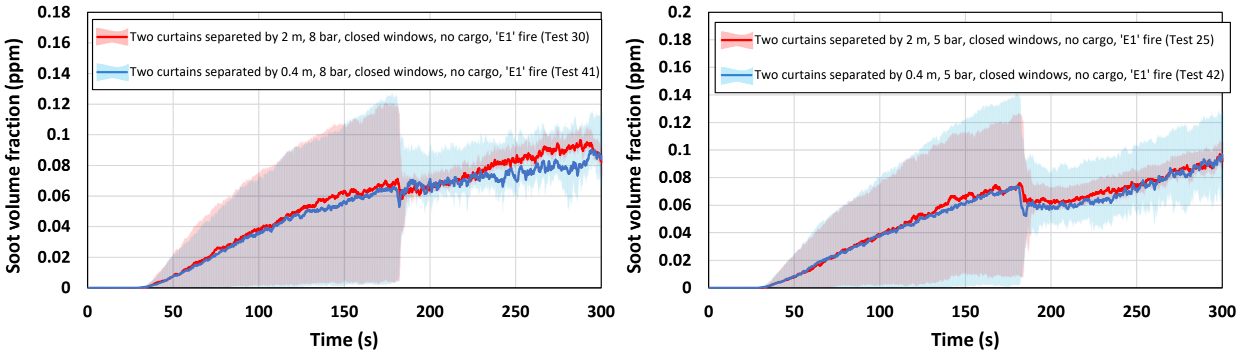

Figure 10. Temporal profiles of soot volume fraction in corridor-end fire tests with two water curtains separated by a distance of either 0.4 m or 2 m, at water pressures of 8 bar (left) and 5 bar (right), with closed windows and no cargo. The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

Given a certain total amount of water flowrate, the choice of two curtains provides more effective smoke containment than the choice of a single curtain, see Figure 11. Accordingly, two curtains operating at 0.2 L/min/nozzle reduce the level of smoke going through the corridor more strongly than a single operating at 0.4 L/min/nozzle. In this case, the two-curtain system has the added benefit of operating at a lower pressure, i.e., 3 bar versus 8 bar, which is valuable not only because it requires a smaller air compressor system but also because it induces less significant turbulent mixing.

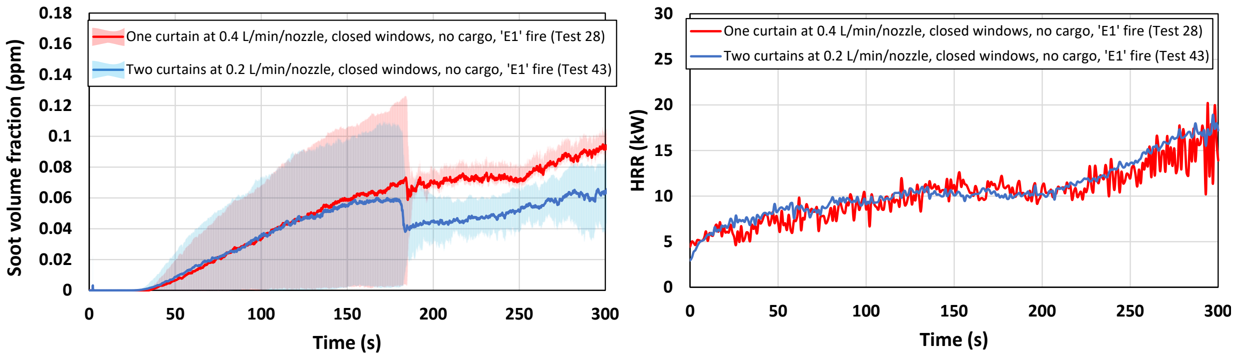

Figure 11. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests with one water curtain operating at 0.4 L/min/nozzle or two water curtains operating at 0.2 L/min/nozzle, with closed windows and no cargo. The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

In the range of water flowrates tested, i.e., from 0.2 to 0.4 L/min/nozzle (or 3 to 8 bar pressure), a water curtain operated using the lowest flowrate provides the highest level of smoke containment when the windows are closed, see Figure 12. This is expected to be due to the lower pressure of such a curtain, inducing less turbulent mixing (note that better mixing near the fire causes the HRR to increase, especially when the windows are open).

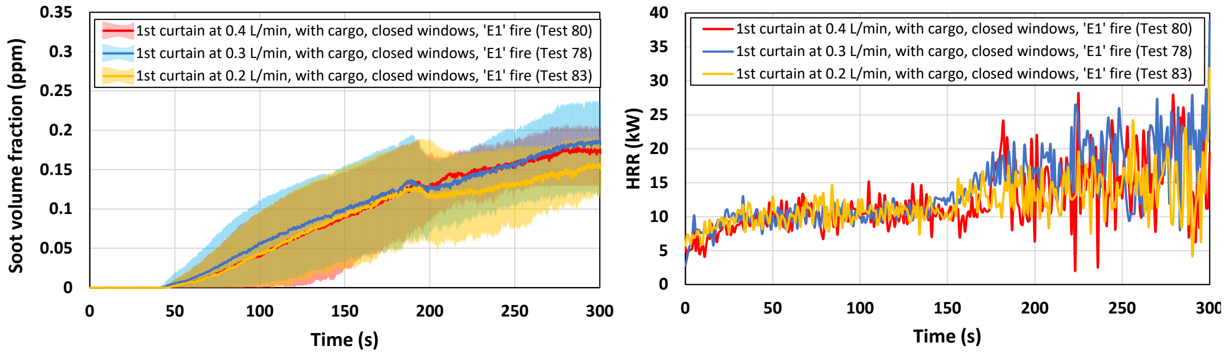

Figure 12. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests with one water curtain operating at either 0.4, 0.3 or 0.2 L/min/nozzle, with closed windows and full cargo loading in the deck. The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

In tests conducted with wood cribs, the activation of a water curtain causes a slight decrease in the HRR, but this increases smoke production at the same, because the pyrolysis of wooden sticks becomes more difficult as the environment is cooled down. Soot volume fraction and mass loss rate is shown in Figure 13 and Figure 14.

Given that the amount of smoke in the wood crib experiments is nearly 10 times lower than the smoke produced in the heptane fire experiments (compare Figure 13 and Figure 14), the increase in the smoke production of the wood cribs by the water curtain is considered acceptable in light of the reduced HRR and probability of flame spread.

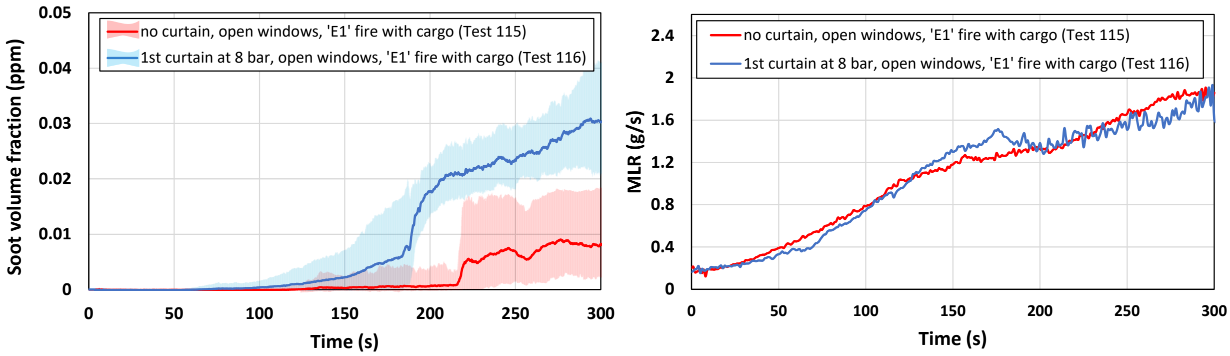

Figure 13. Temporal profiles of soot volume fraction (shown to the left) and Mass Loss Rate (MLR, shown to the right) in corridor-end fire tests with wood cribs used as fuel, with and without water curtain containment (open windows and full cargo loading in the deck). The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

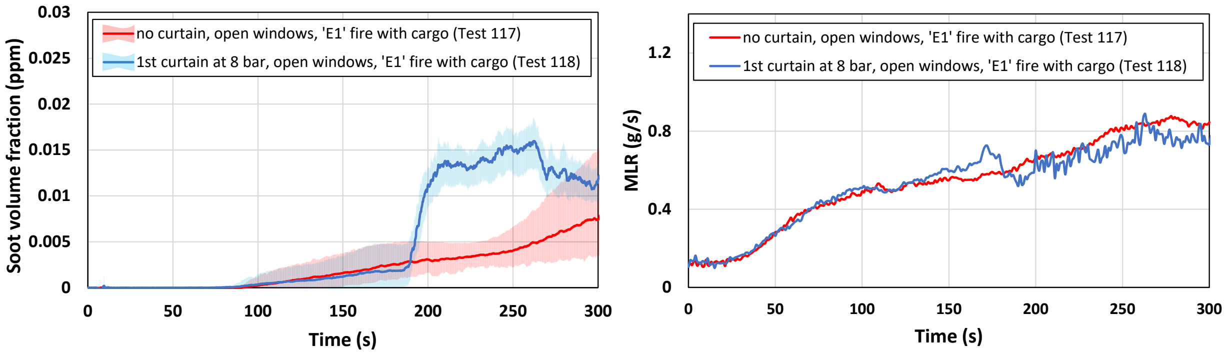

Figure 14. Temporal profiles of soot volume fraction (shown to the left) and mass loss rate (MLR, shown to the right) in corridor-end fire tests with wood cribs used as fuel, with and without water curtain containment (open windows and full cargo loading in the deck). The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

In tests conducted with wood cribs, the activation of a water curtain causes a slight decrease in the HRR (see MLR curve shown in Figure 13 and Figure 14), but this increases smoke production at the same time (see soot volume fractions shown in Figure 13 and Figure 14), because the pyrolysis of wooden sticks becomes more difficult as the environment is cooled down. Given that the amount of smoke in the wood crib experiments is nearly 10 times lower than the smoke produced in the heptane fire experiments (compare Figure 12 and Figure 13), the increase in the smoke production of the wood cribs by the water curtain is considered acceptable in light of the reduced HRR and probability of flame spread.

When the water curtain is combined with a fabric curtain (i.e., both used beside each other at the same time), the curtain is much more effective in creating a subdivision, such that the fire self-extinguishes when the windows are closed, as observed in tests 109-1, 109-2, 113 and 119 (see Figure 15 and refer to the caption of Table 7).

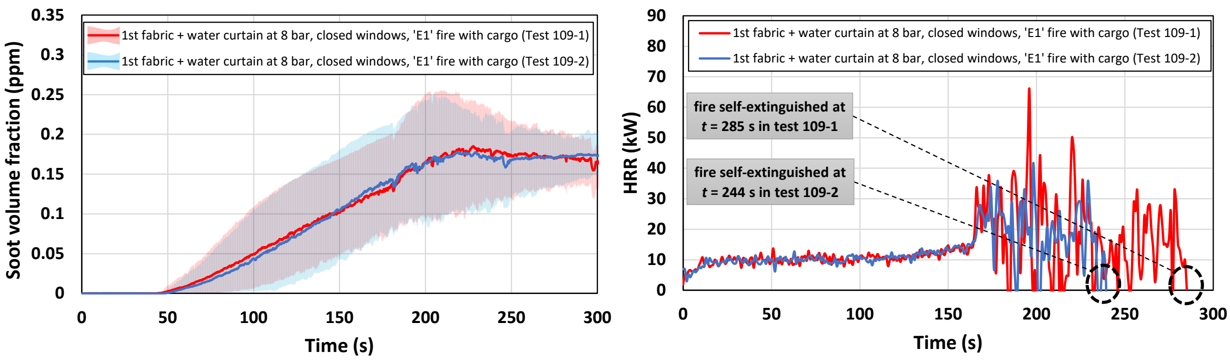

Figure 15. Temporal profiles of soot volume fraction (left) and HRR (right) in corridor-end fire tests contained using the simultaneous use of a fabric curtain and a water curtain (closed windows and full cargo loading in the deck). The average soot volume fraction levels are shown with solid lines while the shading indicates the distribution of soot volume fraction levels across the height (at the location of laser row 'S9' shown in Figure 3).

Overall, the conducted experiments suggest that fires at a closed end of the deck are a worse-case scenario in terms of smoke production and the peak HRR. Therefore, it is recommended to prioritize the prevention and control of such fires.

A 'closed-deck' configuration (with fewer open windows) is found to be much more conservative than an 'open-deck' configuration, ensuring slower fire growth and lower HRRs. In particular, the use of high-pressure water curtains increases the HRR in case of pool fires when the windows are open (by inducing turbulent mixing and rapid pulling of fresh air into the deck through the windows). Solid fuels do not exhibit such an increase in the HRR with open windows. Nevertheless, both solid and liquid fuels will produce lower HRR when the windows are closed. Moreover, when the water curtain is used together with a fabric curtain, the configuration with closed windows makes it possible to cause the fire to self-extinguish due to the lack of oxygen as the fire section is filled with smoke.

Distributing the water to several curtains instead of a single curtain with a high pressure appears to be more effective for smoke containment. For the curtains to operate optimally, the area under the water curtains is best to be free of cargo. This is because when cargo items are placed below a water mist curtain, lots of droplet's land on the cargo items prematurely and cannot float away freely to provide distant radiative shielding and cooling effects. Nevertheless, water curtains create a cool environment within the deck in every scenario and this could potentially reduce the probability of flame spread to sections behind the water curtains.

6.3 Inputs taken from the reduced scale study

Main authors of the chapter: Pascal Boulet, LUL and Antti Virkajärvi, MAR.

Main conclusions from the reduced scale study are the following:

- Radiation attenuation level up to 50% for one curtain and 80% for two curtains were achieved with very low flowrates in reduced scale setup. A large-scale setup might have the potential to provide almost 100% of attenuation. The recommendation is to use water mists (which will produce droplet size in the same range as in the present experiment) and not sprinkler-like systems to take benefit from small droplet injection, while limiting the water flowrate.
- Cost consideration would lead to suggest the use of existing water mist system types in buildings and industry in order to avoid any further development costs and because the expected benefits (cooling of the surroundings, partial containment of smoke, radiation shielding) will be obtained.
- Drawbacks observed in reduced scale (i.e. smoke de-stratification, turbulent mixing with possible effect on the heat release rate of the fire) will occur at the large scale. These effects must be kept in mind before selecting water curtain as a risk control option.
- Present experiments and past experience of the partners lead to the recommendation to leave preferably a free space below the nozzles. FIRESAFE II project[5] even suggested a firebreak about 3 meters between vehicles of neighbouring sections. Authors are aware of the cost that it should induce for operators.
- Some experiments showed that closing the side openings could help to control the fire due to the limitation of the oxygen supply to the fire.

6.4 Practical aspects to be considered with a real scale water curtain

Although water curtain has been a target of recent research projects there are very few commercial applications currently on the market. Movable water curtains have been used by fire brigades to protect buildings or other objects near a fire from radiant heat. However, these systems have been found ineffective as the water consumed by these curtains has been more effective when sprayed directly into the fire.

6.4.1 Practical aspects to be considered about water curtains in ro-ro spaces

According to SOLAS II-2/20.6.1.2 vehicle and ro-ro spaces not capable of being sealed and special category spaces are required to be protected by a fixed water-based fire-fighting system. In fact,

[5] Ship Safety Standards - FIRESAFE II - EMSA - European Maritime Safety Agency (europa.eu)

vessels containing ro-ro spaces considered for subdivision by water curtain typically already possess basic equipment for the integration of water curtain:

- A pump unit supplying water for the fixed fire-fighting system
- Piping connecting the pump unit to the nozzles in the ro-ro space
- Detection system for activating the system

All this equipment can be utilized when designing water curtain (or water wall as it also is called on the market) systems. There may be a need to add capacity to the pump unit to supply water walls simultaneously with the fixed system as well as add section valves for each water wall.

6.4.2 Issues related to the design of a water-based system subdivision

6.4.2.1 General requirements for water-based fire protection systems

A common approach in IMO has been, that for water-based fire protection systems the design parameters of the systems are taken from either prescriptive- or performance-based requirement. For the prescriptive-based systems the requirements are listed in the relevant standard, for example MSC.1/Circ1430 rev1 for ro-ro spaces. In this case these requirements include minimum water discharge densities per deck area and minimum coverage areas depending on installation height. They are common for all prescriptive-based systems independent of system manufacturer.

In case of performance-based systems there are no pre-set design parameters. Instead the design parameters are obtained through full-scale fire tests, which the manufacturer conducts according to the fire test protocol included in the relevant standard, in this case the Appendix of MSC.1/Circ1430 rev1. The protocol defines all necessary information for conducting the fire tests, such as details of the fire load, instrumentation, and pass/fail criteria. The parameters obtained as a result of the fire test include nozzle type, pressure at the nozzle, maximum distance between nozzles and installation height. These are system specific, and different system manufacturers have their own system parameters.

6.4.2.2 Requirements for water wall systems

There are no standards related to water walls/curtains currently available, not for prescriptive- nor for performance-based systems. Should there be a requirement for such systems in the future, detailed regulations regarding the performance, design and installation for these systems need to be developed. These regulations should include at least the following items:

- The requirement for the performance of the water wall/curtain. This would require developing standard parameters for the prescriptive-based systems and a protocol for testing the performance-based systems.
- Minimum operation time of the system.
- Required number of water curtains per deck length. This could be dependent on the cargo type as well as the height of the deck.

It should be noted, that developing such standards typically take time and consume considerable number of developing resources.

6.5 Output for design installation and for cost assessment

The present work shows that water mist can have a significant effect for risk reduction provided some strong recommendations are applied, namely a space free of cargo below the water mist and possibly a closure of the side openings. Both these requirements are too restrictive for the operators, following joined meetings with other work packages (WP03, WP04 and WP05). A partial application of these measures (for example no space left, or no closure of the openings) would not warrant a significant risk reduction, while inducing significant costs.

The costs are directly related to the water mist system and its auxiliary devices. Associated installation and maintenance costs are defined, and this solution will not be assessed further considering the drawbacks observed during the present study. Other solutions based on fabric curtain should be further studied.

7 Fabric curtain as subdivider of ro-ro space

Main authors of the chapter: David Schmidt, RISE, Davood Zeinali and Pascal Boulet, LUL

This chapter is dedicated to fabric curtain and the work that has been conducted during the project. It includes a brief background of the theory of fabric curtains, small- and large-scale study of fabric curtain solution and it also includes a section of feasibility on board.

7.1 Theory of fabric fire protection curtains

Fabric curtains can be subdivided into two main categories, smoke protection curtains and fire protection curtains. Within both categories there are different classifications and time classes to be applied depending on protection goals. These types of curtains are common within building to create smoke and fire barriers between fire zones for stopping fire spread, compartmentation of large spaces or towards escape routes. Fabric curtains could be used as fixed installations always rolled down for smoke evacuation, nevertheless the most applied installations of both smoke and fire curtains are located inside a casing and rolled down in case of signal/alarm which are an active protection. Active curtains could be triggered to release by integration with a fire alarm system sending a signal to the curtain. If a curtain should be rolled out automatically the signal are recommended to be a confirmed fire signal, either by applying a voting principle for detectors or fire alarm triggered by a manual call point. The other alternative is manual release by an operator/crew remotely or locally at the positioning for the curtain.

Smoke protection curtains restrict passage of smoke or are used to direct the smoke for smoke evacuation. In some applications ashore, smoke curtains do not cover the full height but only the upper part, for example in tunnels. Smoke curtains are essential parts in a smoke ventilation system directing the smoke for extraction. Controlling the hot smoke gases could also contribute to stopping fire spread.

Fire protection curtains are mainly used to close wall or ceiling openings for full compartmentation and are likely to be exposed for direct fire. Smoke and fire curtains have a difference in fabric, a fire curtain requires a metal core to be more resistant against direct flames than a smoke curtain. To stop flame spread a fire curtain also shall contain side guides to stop flame spread between curtain and walls/ceiling where it is fixed.

7.2 Reduced scale experimental of fabric curtains

Solid fabric curtains are safety means that has been considered for the subdivision of ro-ro spaces. Fabric curtains can block radiation completely if they are solid and opaque. For smoke shielding, experiments were conducted using a solid fabric curtain to evaluate the containment capability of these curtains, using the setup and fire scenarios the same to those discussed for water curtains (see section 6.2). The fabric curtain was a basic product provided by a company, with no detailed information available regarding its substance. It was not fire rated so there was no classification available. The reduced scale study provided the right geometry for a ro-ro space and allowed evaluation of the containment effect regarding smoke and radiation. The reached temperature, however, in the smoke layer was by far lower than what would be measured at real scale. The temperatures were high enough to provide realistic buoyancy effects (which warrants the correct smoke flow) but too low to investigate a fire performance.

The performed reduced scale tests was using the same set up as in water curtain tests, a solid curtain was simply rolled down instead of activating the water mist. The test scenarios are listed in Table 8.

Table 8. Experiments conducted to assess the effectiveness of fabric curtain.

Test no.	Fuel	Fire size	Fire scenario	Area of openings	Curtain	Flow rate of each nozzle	Row of curtain*	Distance of curtains	Curtain configuration	Cargo load
60	Heptane	5–30 kW	C0⁺	0%	1 fabric curtain	--	1st	--	full height⁺⁺	None
61	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	1st	--	full height⁺⁺	None
62	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	1st	--	car height⁺⁺	None
63˜	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	1st	--	car height⁺⁺	None
64	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	1st	--	full height⁺⁺	None
65	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	1st	--	car height⁺⁺	None
66	Heptane	5–30 kW	E1⁺	5%	1 fabric curtain	--	1st	--	full height⁺⁺	None
67	Heptane	5–30 kW	E1⁺	5%	1 fabric curtain	--	1st	--	car height⁺⁺	None
68	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	2nd	--	full height⁺⁺	None
69	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	2nd	--	car height⁺⁺	None
70	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	2nd	--	full height⁺⁺	None
71	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	2nd	--	car height⁺⁺	None
72	Diesel	3–12 kW	E1⁺	15%	1 fabric curtain	--	2nd	--	full height⁺⁺	None
73	Heptane	5–30 kW	E1⁺	15%	No curtain	--	--	--	--	Full¥
74	Heptane	5–30 kW	E1⁺	0%	No curtain	--	--	--	--	Full¥
75	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	2nd	--	full height⁺⁺	Full¥
76	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	2nd	--	full height⁺⁺	Full¥
84	Heptane	5–30 kW	E1⁺	0%	1 fabric curtain	--	1st	--	full height⁺⁺	Full¥
85	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	1st	--	full height⁺⁺	Full¥
87	Heptane	5–30 kW	E0⁺	15%	1 fabric curtain	--	1st	--	full height⁺⁺	Full¥
88	Heptane	5–30 kW	E0⁺	15%	No curtain	--	--	--	--	Full¥
89	Heptane	5–30 kW	E0⁺	15%	1 fabric curtain	--	1st	--	car height⁺⁺	Full¥
90	Heptane	5–30 kW	E1⁺	15%	1 fabric curtain	--	1st	--	car height⁺⁺	Full¥
91	Heptane	5–30 kW	E2⁺	15%	1 fabric curtain	--	1st	--	full height⁺⁺	Full¥
92-1**	Heptane	5–30 kW	E2⁺	0%	1 fabric curtain	--	1st	--	car height⁺⁺	Full¥
92-2**	Heptane	5–30 kW	E2⁺	0%	1 fabric curtain	--	1st	--	car height⁺⁺	Full¥

* The 1st and 2nd curtain row are fixed at the locations in Figure 3

** Repeated test.

⁺ The fire scenario abbreviations indicate, firstly, the location of the fire: 'E' = end of corridor, and 'C' = centre of corridor; and secondly, the presence of walls that close the corridor from either end: '0' = no walls on either end of the corridor, '1' = one wall closing the corridor on the fire side, '2' = two walls closing the corridor from both ends.

⁺⁺ The full height fabric curtain covers the entire cross-section of the corridor (0.4 m high), while the car height curtain covers only the top 0.26 m, considering that the curtains may drop on cars in reality.

˜ In this test, the curtain was present since *t* = 0 s.

¥ Cargo arrangement is as shown in Figure 5.

7.2.1 Inputs taken from the reduced scale study

The conducted experiments indicate that a solid fabric curtain stops the smoke without disturbing its stratification and it does not affect the HRR as strongly as water curtains do. Moreover, the radiation is blocked completely as the curtain is opaque. Therefore, a solid curtain is deemed appropriate for creating a subdivision in the ro-ro space, although several curtains may be needed along the length of the deck to create multiple subdivisions.

7.2.2 Practical aspects to be considered with a real scale fabric curtain

Although fabric curtain is widely used in buildings there are hard to find marine applications currently on the market. The fact that there are no regulations related to the subdivision of ro-ro spaces leads to the need for detailed regulations regarding the performance, design, and installation for these systems. These regulations should include the requirement for the performance of the curtain, for example similar to the fire integrity (A-0, A-30, or A-60) for horizontal containment. This would require developing a protocol for testing the systems and curtains should be subject for FTP Code.

Installing a set of fabric curtains in a ro-ro space needs the area under the curtains to preferably be free of cargo for the curtains to operate fully down. If the curtain is only partially rolled down, there is a delay in the smoke propagation. Moreover, the experiments show that when the solid curtain drops only to the car height level, the peak HRR is nearly 30% higher compared to when the curtain drops to the floor level (if there are openings). In any cases, from this reduced scale study it is recommended that the fabric curtain is used together with a water curtain. Experiments indicate that in configurations with closed openings, a combined fabric and water curtain can cause the fire to self-extinguish due to the lack of oxygen as the fire section is filled with smoke.

Additional issues to be considered are the interaction with the side openings, as smoke exhaust will be modified once the curtain will be rolled down, the interaction with the ventilation system and the possibility of passing through a rolled down curtain, for evacuation or other purpose. Also, training of the crew in how to use the curtain(s) will be an aspect to consider.

7.3 Fabric curtain in a ro-ro space

Subdivision of a ro-ro space can be performed either longitudinal or transversal within the ro-ro space or to be used for separation between weather deck and an open ro-ro space.

Longitudinal mounting would allow the curtain to be rolled down and covering the full height of the ro-ro space without any additional requirements with regards to loading procedures. On a ro-pax vessel there are lanes for the cargo to be rolled on, and between those lanes there are many times a natural separation between the cargo allowing the curtain to roll down, see example in Figure 16.

Figure 16. Example of longitudinal gap between cargo in a ro-ro space.

The picture shows an example of natural segregation between cargo where a longitudinal mounted curtain would be allowed to drop all the way down to deck. In some cases side mirrors on trucks or cars are interfering with the break although the weight of this wide curtain would most probably allow the curtain to roll down anyway.

For a transversal solution, if the curtain should drop down fully to deck, there are required to be a fire break of at least 100 mm allowing the curtain to pass between the loaded cargo. Transversal natural division creating a fire break does not exist today and needs to be created with regards to the loading of cargo. This will reduce the flexibility in loading cargo for the ro-ro space. See Figure 17 for an example where a transversal mounted curtain would require different arrangement for cargo to create a gap between the cargo allowing the curtain to roll down. A solution for transversal fabric curtain can be to have a striped curtain, or a curtain that is not fully rolled down, a curtain that is allowed to stop on top of cargo.

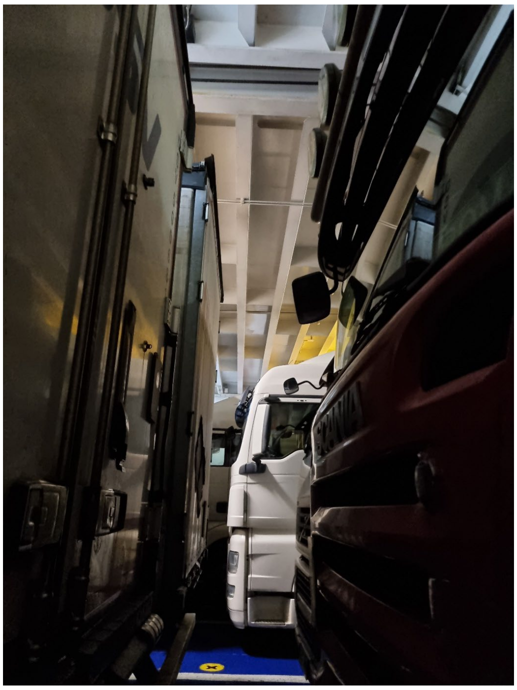

Figure 17. Challenge for transversal subdivision of ro-ro space loaded with cargo

Four different solution concepts for subdivision of the ro-ro space with use of fabric curtains were evaluated:

a) Solid curtain, longitudinal mounting, fully rolled down.

b) Solid curtain, transversal mounting, fully rolled down.

c) Solid curtain, transversal mounting, partly rolled down.

d) Striped curtain, transversal mounting, partly/fully rolled down.

The four concepts are illustrated in Figure 18.

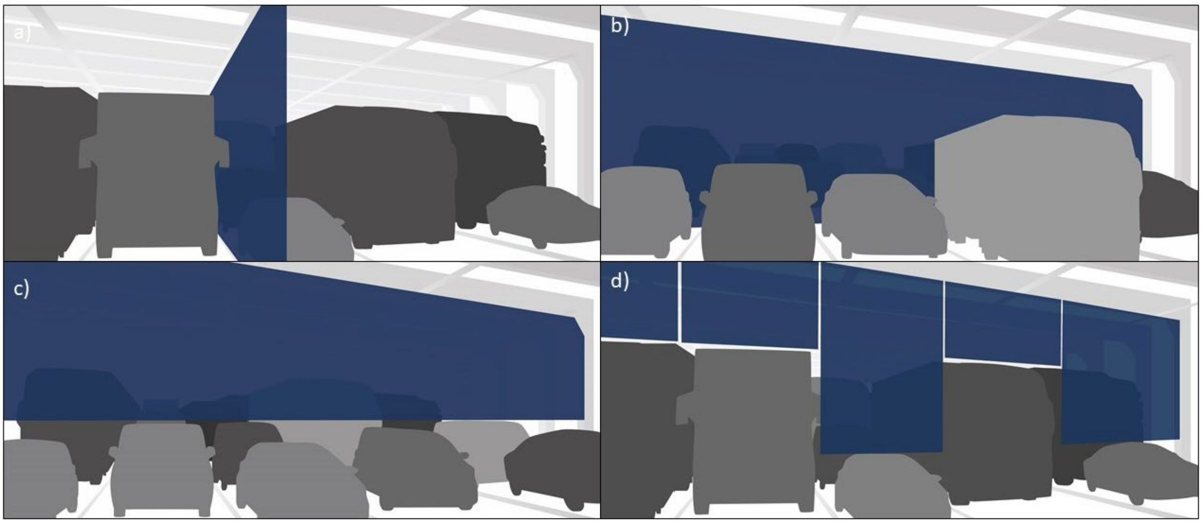

Figure 18. Four different solution concepts for fabric curtains; a) Solid curtain, longitudinal mounting, fully rolled down; b) Solid curtain, transversal mounting, fully rolled down; c) Solid curtain, transversal mounting, partly rolled down; d) Striped curtain, transversal mounting, partly/fully rolled down

7.3.1 Demonstration on board

Main authors of the chapter: David Schmidt, RISE

Presentation of the fabric curtain solution was performed on board a ship from LASH FIRE partner.

During the onboard demonstrations it was clear fitting a curtain solution on existing vessels will be very challenging due to all roof mounted equipment and layout of girders. To not conflict for this equipment the casing for the curtains needs to be fitted towards the girders which will conflict with the available height for loading. A ro-ro space is optimized with regards to loading height and in many cases ordered according to these there are no alternative to mount the casing conflicting with the available height for cargo. To make space available for the casing for the curtains there needs to be a lot of re-construction of the fitted equipment in roof and in other cases the space is too limited. A range of vessels also have beams both transversal and longitudinal conflicting to mount the casing above the lowest level of the beams.

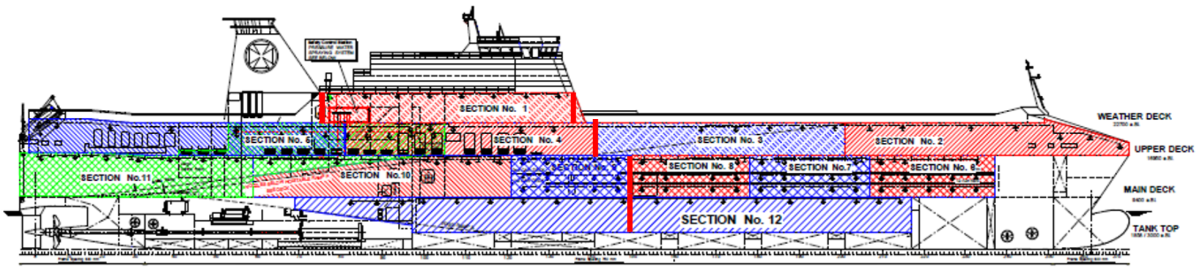

Figure 19. Illustration of subdivision of ro-ro deck for Magnolia Seaways. Subdividing Upper deck, Main deck and Tank top into fore and aft sections and shield superstructure from a fire at fore or aft weather deck.

Different loading scenario was observed to evaluate the effect of creating a fire break with regards to loading on board. During loading of cargo it was observed according to existing loading there are no natural placing for a curtain with regards to existing break between cargo. Gaps between cargo shifts a lot between different voyages observed in the project. In order to have a straight line of minimum 100 mm there will be a requirement for a loading plan to arrange this. Due to this reason existing vessels are excluded from a fabric curtain solution.

Apart from feasibility and installation assessments performed on board Magnolia Seaways additional evaluations was performed on board Stena Jutlandica for verification of stowing with regards to create a straight line of at least 100 mm across the ro-ro space allowing a curtain to drop down to deck.

Trucks are generally stowed very tight next to each other. One way of stowing is to have the cars in the front in some lanes and then filled up with trucks. The variety of cargo between the different trips challenge the stowing if a curtain is mounted and requires a fixed positioning. For pictures from different ro-ro spaces and challenges for a fabric curtain see Annex B.

Two of the four concepts were further assessed with installation design aspects, see the following section.

7.3.2 Operational, design and construction aspects

Main author of the chapter: Vito Radolovic, FLOW and David Schmidt, RISE

7.3.2.1 Solid curtain, transversal mounting, fully rolled down

The solid curtains are arranged to follow the drencher zones where the curtains shall divide each ro-ro space in two and additionally close the forward and aft opening of open ro-ro spaces towards the weather deck, where applicable. The longer the curtain the bigger the axle needs to be to hold up the weight of the curtain and to not loosen the straightness. Additional loading bearings are foreseen to be installed every 1.5m to bare the weight of the curtain.

From electrical side the tubular motors are connected to a control panel which shall be mounted in adjacent to the curtain. To this panel a 230 VAC feeder must be connected. The panel shall also be integrated with the fire alarm system which requires a signal cable to the control panel. The curtains are gravity fail safe which means they will roll down in case of a power loss. It is hold up by magnets which are feed with 24 VDC from the control cabinet. The control cabinet also consist of capacitors taking care of power peaks and drops up to 5 minutes. The full roll out of the curtain takes 30 seconds for a height of 5 m.

The curtain is fixed inside a galvanized metal casing. Inside the casing the curtain is rolled up on an axel with a tubular motor.

Illustration with measurements for curtain is shown in Figure 20.

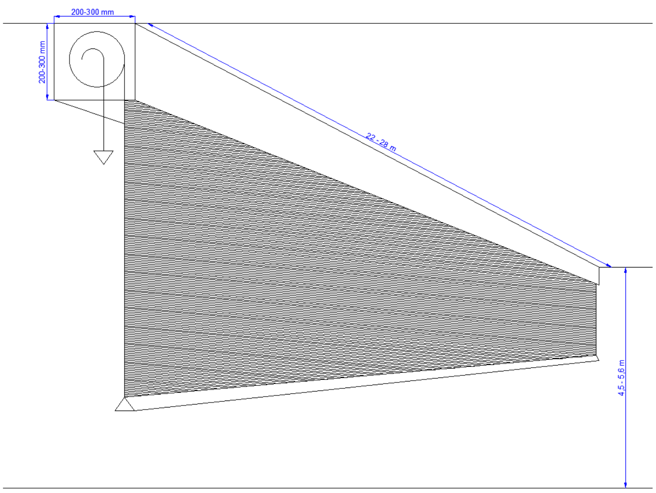

Figure 20. Illustration of a solid curtain for a ro-ro deck

The curtain itself needs only a few centimetres free space in a straight line for rolling down, but a space of approximately 100 mm should be taken into account to allow free passage for the curtain down to the deck. Need for a gap in cargo stowage on deck will significantly influence on the cargo handling operations and cargo loading flexibility. Further, cargo capacity on the deck will be reduced which will have significant impact on the cost (loss of revenue).

From operational perspective, the gravity fail safe option may lead to unexpected injuries to crew and passengers and cargo damage. It is recommended that the control of the curtain should be performed from a remote location such as fire control station or similar. Additional crew training will be necessary.

The curtain is assumed integrated in the ship structure to avoid interference with the clear height. Thus, local structural adjustments are considered.

The curtain shall be applicable for ro-pax and ro-ro cargo newbuildings.

The integration on the generic ro-pax ship Stena Flavia considers installation of the curtain system within ro-ro spaces at Deck 1, Deck 2, Deck 3, Deck 4, and Closure of aft openings at Deck 3, as illustrated in Figure 21.

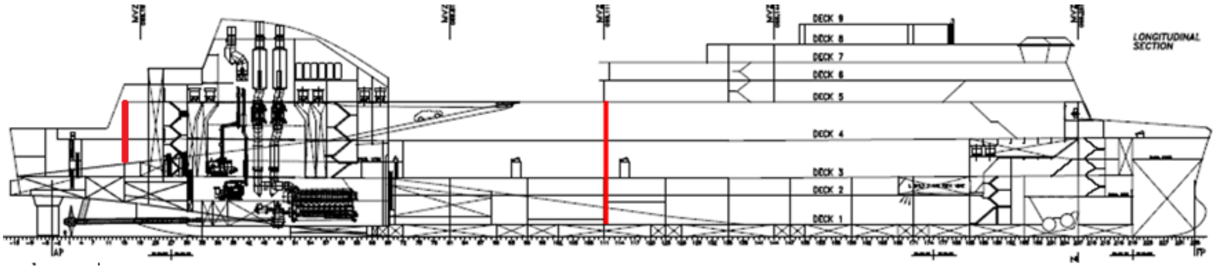

Figure 21. Vertical subdivision – Stena Flavia

The aft opening is a large opening divided by a centre casing, thus requiring two closing devices. One of the devices will extend further down than the other due to the ramp that is positioned at a lower level than the normal Deck 4 level.

Total of 350 m of power cables and 650 m of signal cables are approximated.

Structural modification of Deck 2 structure, where the web height is lower than the required height for curtain installation, is considered manageable for new designs where ship height or reduction of clear height (keeping same ship height) would be necessary with respect to the generic ship arrangement.

The integration on the generic ro-ro cargo ship Magnolia Seaways considers installation within ro-ro spaces at Tank top, Main deck, Upper deck, and Closure of aft and forward openings at Weather deck, as illustrated in Figure 22.

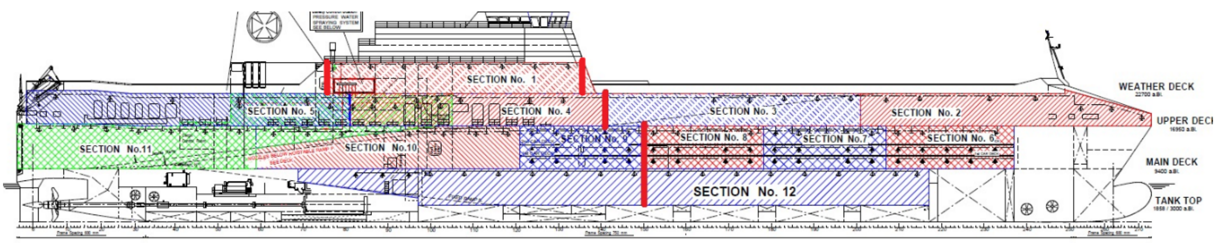

Figure 22. Vertical subdivision – Magnolia Seaways

The arrangement of curtain at Main deck is in the area of movable decks, where specific arrangement in way of required clearance between movable deck panels is assumed manageable for newbuilding's. Total of 300 m of power cables and 400 m of signal cables are approximated.

7.3.2.2 Striped curtain, transversal mounting, fully/partly rolled down

The proposed striped curtain solution considers sub-dividing the ro-ro deck, by a transversally mounted curtain. The stripes are divided per lane, one lane has one curtain. The intention of the striped curtain is to stop potential smoke spread along the whole ship. The fabric consists of a smoke rated textile. The project proposes to use one curtain for subdivision per ro-ro deck.

The curtain is fixed inside a galvanized metal casing. For this solution there will be one casing per lane. Inside the casing the curtain is rolled up on an axel with a tubular motor. Each complete casing with curtain would weigh about 100 kg, this will for an 8-lane wide ro-ro space add extra 800 kg. Between each curtain there will be a gap of 7 centimetres.

Illustration with measurements of a striped curtain is shown in Figure 23.

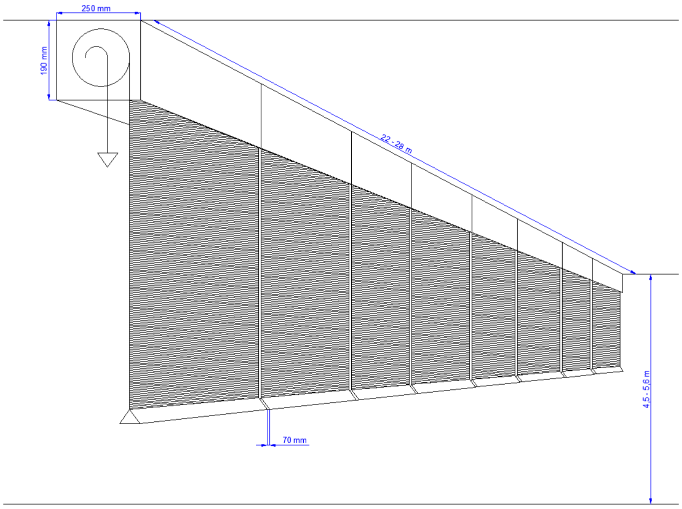

Figure 23. Illustration of a striped curtain for a ro-ro deck

The curtain shall roll out only in case of a confirmed fire. Due to the separation for each lanes the curtain will drop down to different heights depending on the height of cargo placed underneath. Recommendation is to roll out the curtain manually due to the risk of lowering the curtain on sensitive cargo, such as car roof, due to the weight of the curtain.

The proposed solution of a fabric curtain shall be applicable for ro-pax and ro-ro cargo newbuildings.

For the striped curtain operation, a clearance on deck in line with the curtain is not required as the curtain is lowered up to the top of the cargo instead of fully dropped down and there is not expected to be any cargo loss. The operational aspects are similar as for solid curtain. Installation of a striped curtain, however, is questionable within ro-ro spaces with movable decks and may increase the complexity of the deck arrangement as well as cargo loading/unloading operation leading to breaks in cargo stowage.

The curtain is assumed integrated in the ship structure to avoid interference with the clear height. Thus, local structural adjustments are considered.

Total of 750 m of power cables and 1800 m of signal cables are approximated for Stena Flavia, where total of 800 m of power cables and 1500 m of signal cables are approximated for Magnolia Seaways.

Structural modification of Deck 2 structure, where the web height is lower than the required height for curtain installation, is considered manageable for new designs where ship height or reduction of clear height (keeping same ship height) would be necessary with respect to the generic ship arrangement. This aspect has, however, not been considered in the cost assessment.

The arrangement of a fabric curtain at Magnolia Seaways' main deck is in the area of movable decks, where the installation of a striped curtain is found to be hardly manageable to avoid a break in the cargo stowage. Further, as the curtain shall be rolled up to the cargo it is not understandable how shall this be executed on the deck below the movable deck.

Curtain arrangement and operation, considered for the cost assessment, is to lower the curtain up to the cargo on the lowermost deck, leading to a break in the cargo stowage on the upper movable deck(s). This leads to an increased complexity of the deck arrangement, cargo loading/unloading operation and loss of revenue.

Independent of the system and ship type the following costs were considered:

- Investment cost,
- Operation cost
- inspections, testing, and maintenance,
- end of life cost.

7.4 Large scale validation of fabric curtain

Main authors of the chapter: Kim Olsson, Magnus Bobert, Örjan Westlund, RISE

It was decided to test the striped curtain, transversal mounting, fully/partly rolled down in a large-scale setup. The following sections describes the large-scale tests that was conducted to validate striped fabric curtain as a solution for subdivision of ro-ro spaces. Tests was performed 7-30 September 2022, at Guttasjön outside Borås (Sweden).

7.4.1 Objective of the large-scale test

The objective of the test was to determine the containment effect with subdivision by the use of striped smoke curtains segments covering each lane in a ro-ro space, see Figure 24.

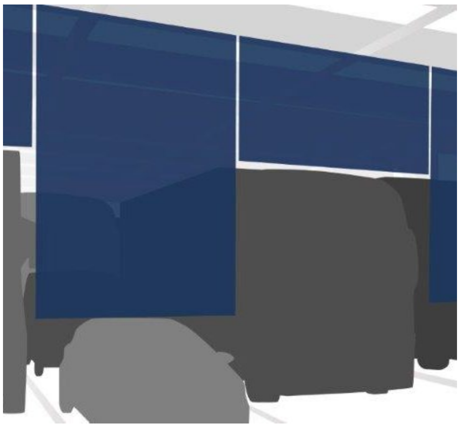

Figure 24. Concept solution tested in large-scale

Test was designed to:

1) determine effect of different loading scenarios.

2) evaluate ability to pass rolled down curtain.

In comparison with the solution with a curtain covering the full width of the space a striped curtain advantage with respect to flexibility for cargo also have some challenges:

- Verifying the effect of openings between curtains caused by the casing of the curtains mounted next to each other.
- Verifying the effect of additional openings caused by cargo placed underneath the curtain hindering the curtain to drop all the way to deck.

Textile curtains are mainly used for inside building, for big dimensions or architectural design. They are designed to confine a volume in terms of smoke and/or fire, by closing an opening.

They are usually used without sprinklers and have the advantage to have a small footprint as they stay open and close only in case of necessity and have the advantage to be lighter compared to a steel rolling shutters due to their low weight.

7.4.2 The tested fabric

Main authors of the chapter: Pierrick Mindykowski, RISE

Small scale material tests were performed to study fire resistance and evaluate how close to the fire source the fabric curtain can be used in the large-scale tests, so it will be able to use the curtain in several trials.

The tested fabric was categorized as a textile smoke apron. It is a coated glass filament fabric designed for high time classes temperature loads up to 1100°C and classified according to DIN EN 12101-1. Tests were performed without casing holding the fabric, solution with casing verified in suppliers' tests according to DIN EN12101-1 and are not the objective of performed test for LASH FIRE. In the bottom of the curtain a steel bar is mounted as weight stretching down the curtain and mitigate deflection.

7.4.2.1 Cone calorimeter tests of curtain

The cone calorimeter test (according to ISO 5660-1) consists of applying a certain level of radiant heat flux to a sample and observing if, in presence of a small igniter, the sample will ignite. The ignition should be taken as a sustainable visible flame for some seconds.

The tested fabric present different colours on each face, light and dark. In order to judge if the colour plays any role in the fire property of the curtain, it was decided to test the curtain on each face. Four different levels of radiant flux were used. The matrix of tests is the shown in Table 9.

Table 9. Test matrix for fabric in cone calorimeter tests (ISO 5660-1)

Flux in kW/m^2	Side of the curtain	Ignition
5	Dark	No ignition
10	Light	No ignition
10	Dark	No ignition
20	Light	No ignition
20	Dark	No ignition
50	Light	No ignition
50	Dark	No ignition

For the current study, no visible flame has been observed, even for the tests with 50 kW/m^2 for 50 minutes. It was concluded that the curtain material was suitable and would most likely sustain repeated full-scale tests.

7.4.3 The test area

The test was conducted at Guttasjön. Guttasjön is a modern facility of 65 000 sqm used for rescue and fire exercises. The large-scale validations were performed in an embankment which collects and cleans the used water.

a

Figure 25. Overview of test area at Guttasjön

7.4.4 Test setup

The test setup consisted of two containers welded together and with the interior bulkhead removed to form a simulated ro-ro space with dimensions 12 x 2.3 x 4.6 m (length x height x width), see Figure 26 and Figure 27. A total of 12 openings of 0.5 x 1 m each was symmetrically distributed along the container to accommodate ventilation for the fire and ability to observe the inside of the container during the tests.

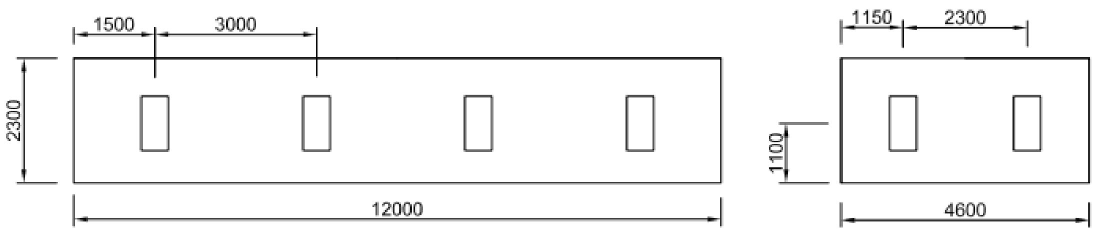

Figure 26. Schematic of the sides and ends of the container.

Figure 27. Picture of the container used in the tests.

The reason for the openings is that it is simply impossible to start and sustain a fire in a completely closed container and get any useful information from the test. Furthermore, the openings can be seen as an attempt to simulate the scale of ro-ro spaces which is much larger in reality.

In one end of the container space, a pool fire was located as fire source. A pool with dimensions 590 x 150 mm (diameter x height) was filled with 5 litres of water and 27 litres of heptane (corresponding to a 100 mm fuel depth). The pool was placed at the centre line of the container space, 1500 mm from the short end of the space.

Two curtains were mounted, one for each lane of the container space, and thus the solution was as the concept of a striped curtain. The curtains were placed in the middle of the space, see Figure 28 and Figure 29. The distance between the two curtains was 100 mm. The distance from the curtain and the sides of the container was 70 mm, however a 50 mm wide wooden beam was fastened to the side to prevent excessive leakage. The gap between the curtains and deckhead was filled with mineral wool.

The vehicles used in the test consisted of a passenger car and a van. The vehicles were defueled and stripped of any parts that could cause danger to the personnel in case the vehicles caught fire.

Figure 28. Picture of the inside of the container with curtain in the middle.

Figure 29. Picture of the fabric curtains positioned at mid length of the container.

7.4.5 Fire test procedures

The pool fire source was ignited at the start of the test. The test ended when the pool fire no longer had any fuel – usually about 25 minutes.

Since the tests were performed outside both wind speed, wind direction and outside temperature affected both the temperature measurements and the pool fire itself (mainly due to oxygen entrainment). All test with cars were replicated on different days to account for this variability.

7.4.6 Instrumentation and measurements

Gas temperature measurements using thermocouples was used for measuring the temperature of the air and/or smoke gases inside the container during the tests. Thermocouples were used to measure temperature at different heights and distances from the curtain. The thermocouples were placed just in front of the curtain on the fire source side and right behind the curtain to be able to evaluate the temperature decrease over the curtain. A set of thermocouples was also placed half a meter from the end of the container.

The container space was instrumented with a total of 36 pcs 0.5 mm thermocouples of type K. Thermocouples were positioned at a distance of 500 mm on each side of the fire curtain and at a distance of 500 mm from the short side of the container without fire source. Each tree of thermocouples was comprised of 4 thermocouples measuring the temperature 100 mm below the deckhead and equal increments of 600 mm downwards to the deck.

The thermocouples were distributed in three cross sectional planes of the container as seen in Figure 30 and Figure 31.

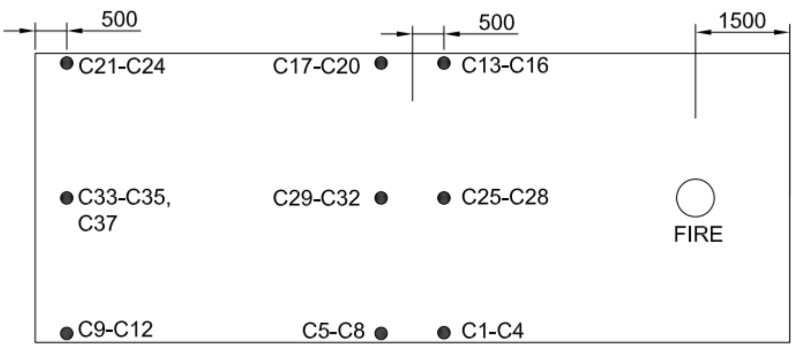

Figure 30. Schematic of the thermocouple instrumentation. Top view.

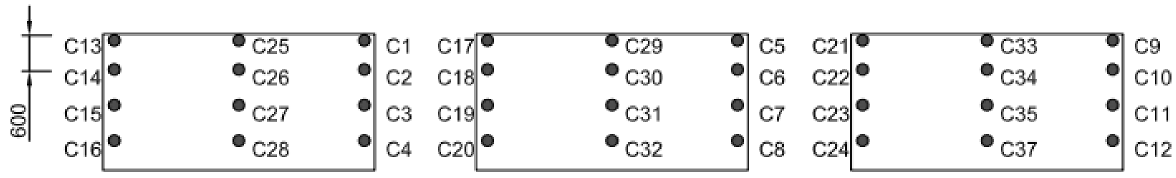

Figure 31. Schematics of the thermocouple instrumentation. Cros sectional views.

7.4.7 Test scenarios

Five different test scenarios were evaluated:

1. No vehicles. Both curtains up.
2. No vehicles. Both curtains down.
3. One passenger car. Both curtains down.
4. One passenger car and one van. Both curtains down.
5. One van. Both curtains down.

Before the test series started, a technician with fully equipped firefighting gear navigated through the container with and without the fire curtains down. In both scenarios, the time to move from one short end of the space to the other was approximately 10 seconds.

7.4.7.1 Test scenario 1. No cars. Fire curtains up

The steel profiles holding the curtains were 100 mm high, together with the curtains a total height of 270 mm was covered. The gap between the curtains was 100 mm, see Figure 32. The test was performed 2022-09-19 and lasted 25 minutes.

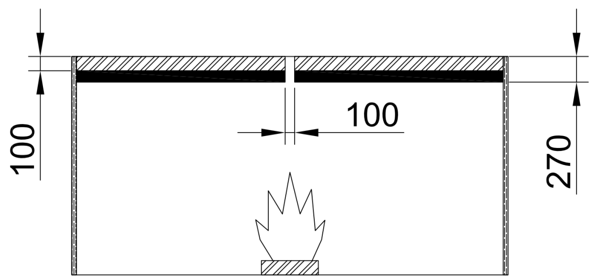

Figure 32. Schematic of the test scenario 1 where there are no cars in the space and the curtains were up.

7.4.7.2 Test scenario 2. No cars. Fire curtains down

In this scenario no cars were present, and the curtains were rolled down. A total height of 2225 mm was covered, see Figure 33. The test was performed 2022-09-19 and lasted 28 minutes.

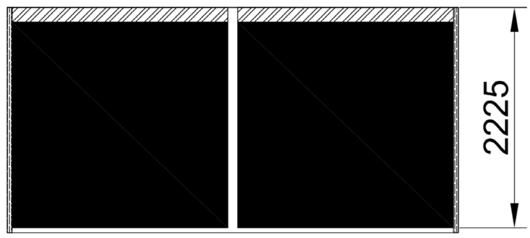

Figure 33. Schematic of test scenario 2 where there were no cars in the space and the curtains were down.

7.4.7.3 Test scenario 3. One passenger car. Fire curtains down

In this scenario one passenger car was positioned at the centre of the lane in the middle of the container, and the curtains were down. The total height of 2225 mm was covered by the fire curtain in one of the lanes whilst the lane with the car was covered by 775 mm fire curtain, see Figure 34.

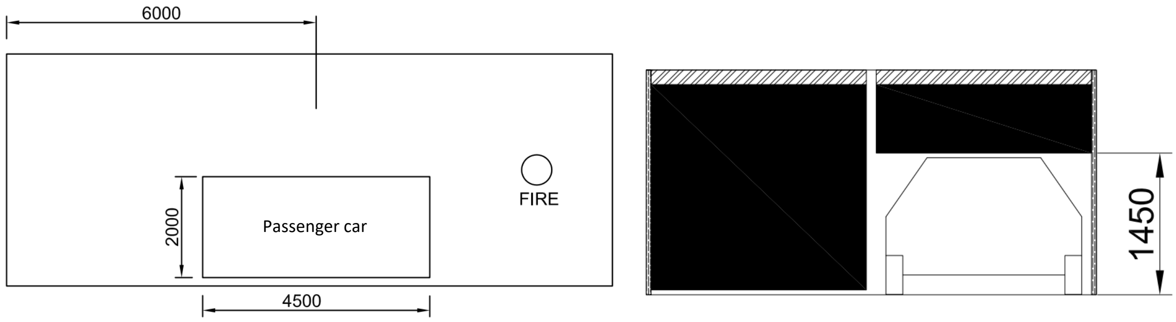

Figure 34. Test scenario 3. One passenger car. Fire curtains down. Top view to left. Cross sectional view to right.

Two tests were performed this way, the first 2022-09-19 which lasted 25 minutes. The second test was performed 2022-09-20 and lasted 28 minutes. A picture from the test in shown in Figure 35.

Figure 35. Picture of test scenario 3 set up.

7.4.7.4 Test scenario 4. One passenger car and one van. Fire curtains down

In this scenario one passenger car and one van were positioned at the centre of respective lane in the middle of the container, and the curtains were rolled down. A total height of 375 mm was covered by the fire curtain in one of the lanes whilst the other lane was covered by 775 mm fire curtain, see Figure 36.

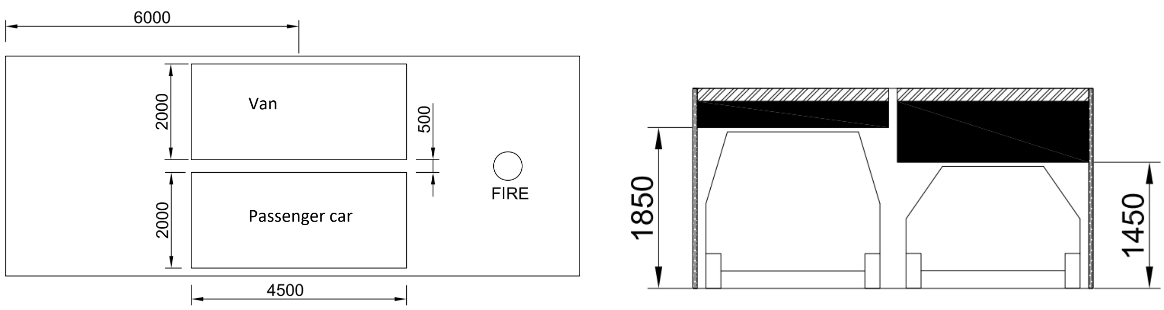

Figure 36. Test scenario 4. One passenger car and one van. Fire curtains down. Left) Top view. Right) Cross sectional view.

Two tests were performed this way, the first 2022-09-20 which lasted 26 minutes. The second test was performed 2022-09-21 and lasted 25 minutes. A picture from the test is shown in Figure 37.

Figure 37. Picture of test scenario 4 set up.

7.4.7.5 Test scenario 5. One van. Fire curtains down

In this scenario a van was positioned in one lane and the curtains were rolled down. A total height of 375 mm was covered by the fire curtain in the lane with the van whilst the other lane was covered at the total height by 2225 mm fire curtain, see Figure 38.

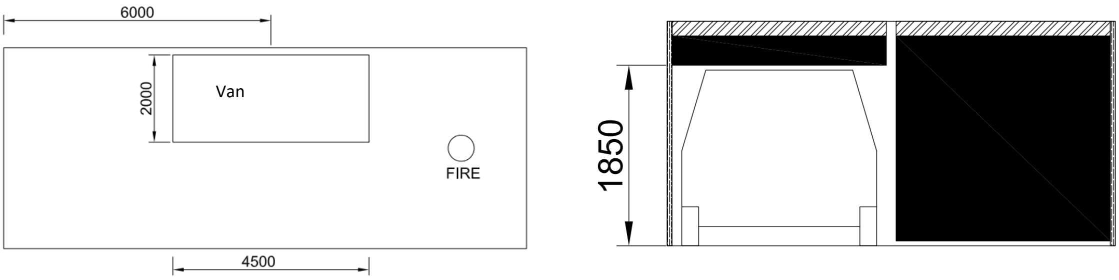

Figure 38. Test scenario 5. One van. Fire curtains down. Left) Top view. Right) Cross sectional view.

Two tests were performed this way, the first 2022-09-21 which lasted 18 minutes. The second test was performed 2022-09-22 and lasted 20 minutes. A picture from the test is shown in Figure 39.

Figure 39. Picture of test scenario 5.

7.4.8 Results from large scale test with fabric curtain

7.4.8.1 Test scenario 1. No cars. Fire curtains up

In Figures A.1-A.4 in Annex A, are graphs which show the average of the thermocouples in each cross-sectional plane at different heights i.e. legend “Fire side curtain” is the average temperature of thermocouples C1, C25 and C13, legend “Cold side curtain” is the average of thermocouples C5, C29 and C17 and legend “Cold side” is the average of thermocouples C9, C33 and C21.

In Figure 40 the moving average (MAV, using a 1-minute window) of the temperature difference across the fire curtains i.e., the triad of thermocouples at each side of the fire curtain, at the various height levels are shown.

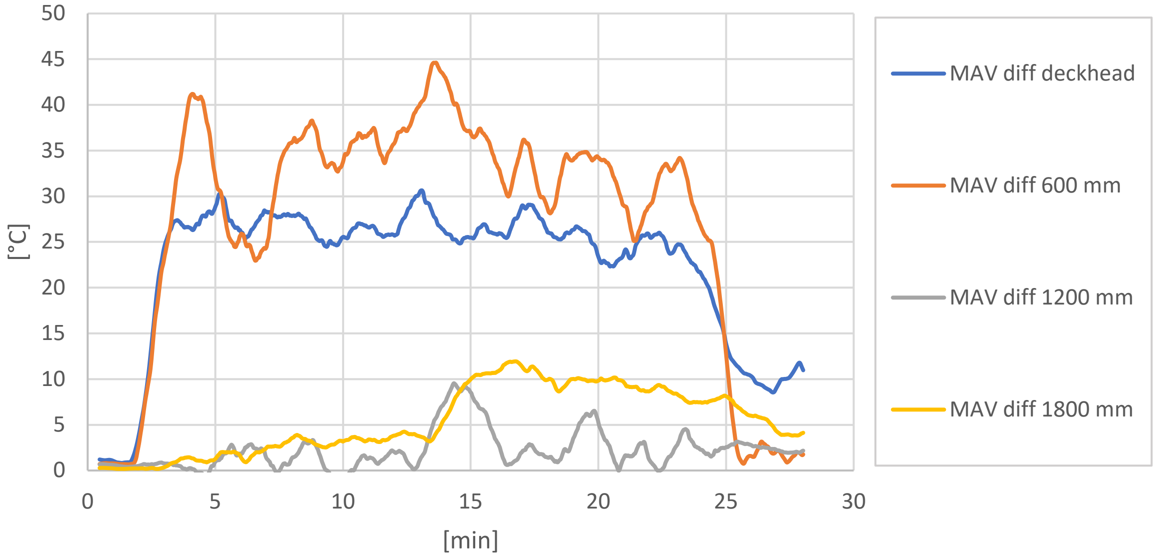

Figure 40. Test scenario 1. The moving average of the temperature difference across the fire curtains at the various height levels

7.4.8.2 Test scenario 2. No cars. Fire curtains down

In Figures A.5-A.8 in Annex A, are graphs which shows the average of the thermocouples in each cross-sectional plane at different heights i.e. legend “Fire side curtain” is the average temperature of thermocouples C1, C25 and C13, legend “Cold side curtain” is the average of thermocouples C5, C29 and C17 and legend “Cold side” is the average of thermocouples C9, C33 and C21.

In Figure 41 the moving average (MAV, using a 1-minute window) of the temperature difference across the fire curtains i.e., the triad of thermocouples at each side of the fire curtain, at the various height levels are shown.

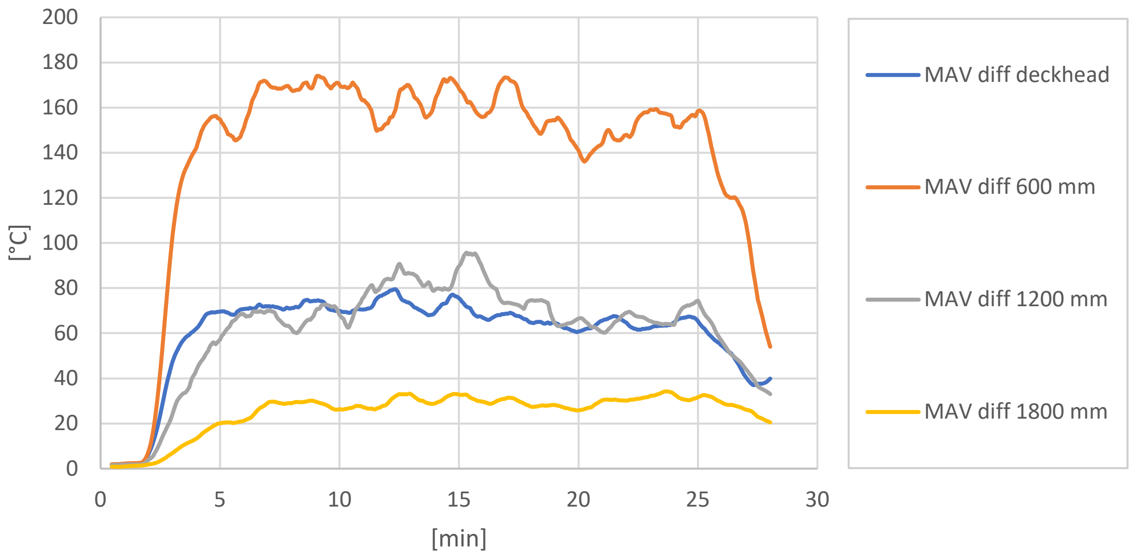

Figure 41. Test scenario 2. The moving average of the temperature difference across the fire curtains at the various height levels.

7.4.8.3 Test scenario 3. One passenger car. Fire curtains down

In Figures A.9-A.16 in Annex A, are graphs which show the average of the thermocouples in each cross-sectional plane at different heights i.e., legend "Fire side curtain" is the average temperature of thermocouples C1, C25 and C13, legend "Cold side curtain" is the average of thermocouples C5, C29 and C17 and legend "Cold side" is the average of thermocouples C9, C33 and C21.

In Figure 42 and Figure 43 the moving average, from the first and second test respectively (MAV, using a 1-minute window), of the temperature difference across the fire curtains i.e., the triad of thermocouples at each side of the fire curtain, at the various height levels are shown.

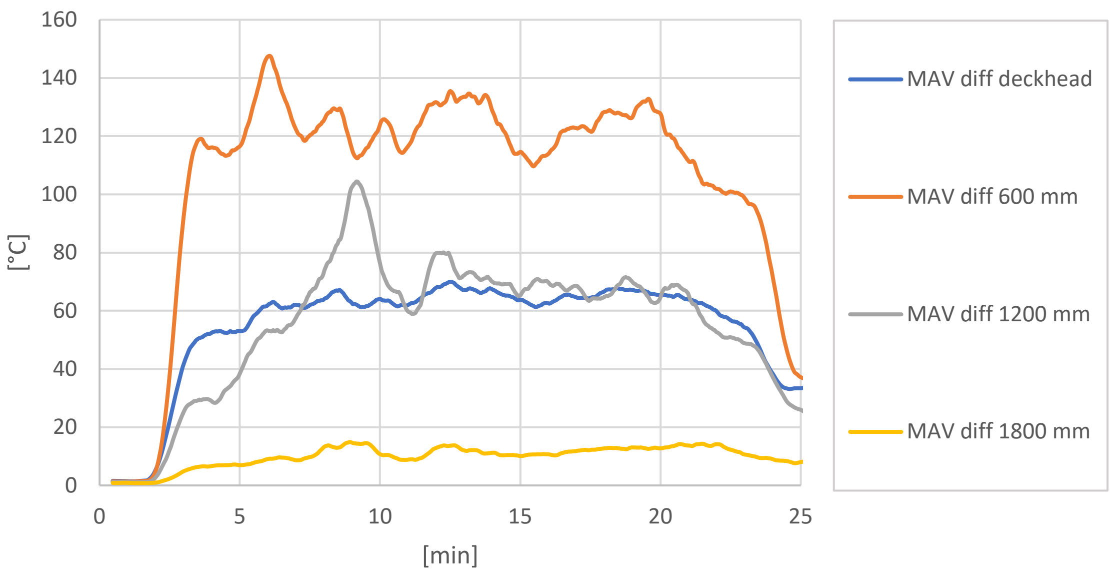

Figure 42. Test scenario 3. The moving average of the temperature difference across the fire curtains at the various height levels. First test, 2022-09-19.

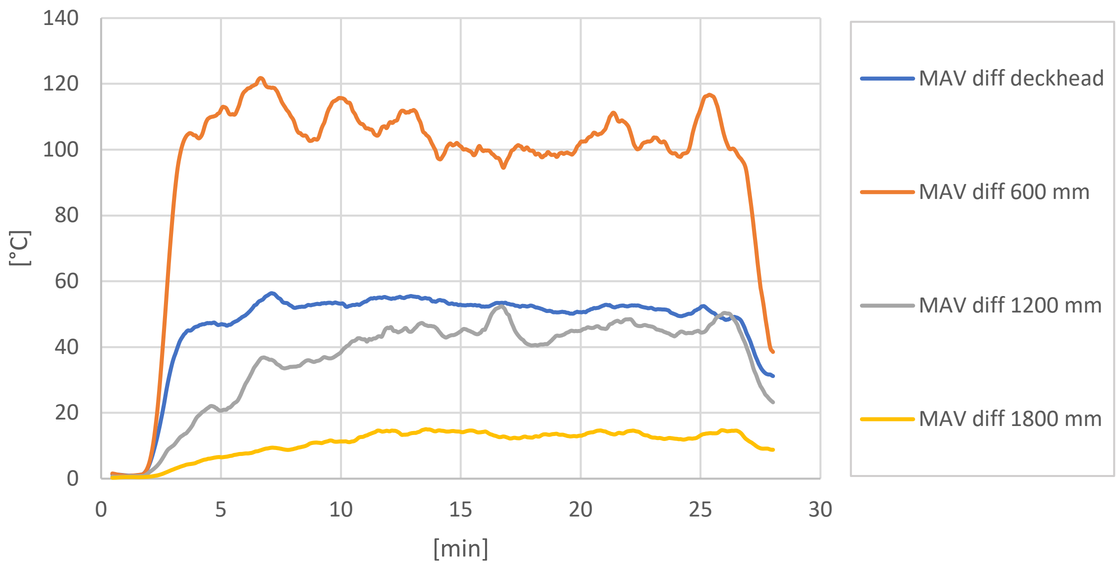

Figure 43. Test scenario 3. The moving average of the temperature difference across the fire curtains at the various height levels. Second test, 2022-09-20.

7.4.8.4 Test scenario 4. One passenger car, one van. Fire curtains down

In Figures A.17-A24 in Annex A, are graphs which shows the average of the thermocouples in each cross-sectional plane at different heights i.e. legend "Fire side curtain" is the average temperature of thermocouples C1, C25 and C13, legend "Cold side curtain" is the average of thermocouples C5, C29 and C17 and legend "Cold side" is the average of thermocouples C9, C33 and C21.

In Figure 44 and Figure 45 the moving average, from the first and second test respectively (MAV, using a 1-minute window), of the temperature difference across the fire curtains i.e. the triad of thermocouples at each side of the fire curtain, at the various height levels are shown.

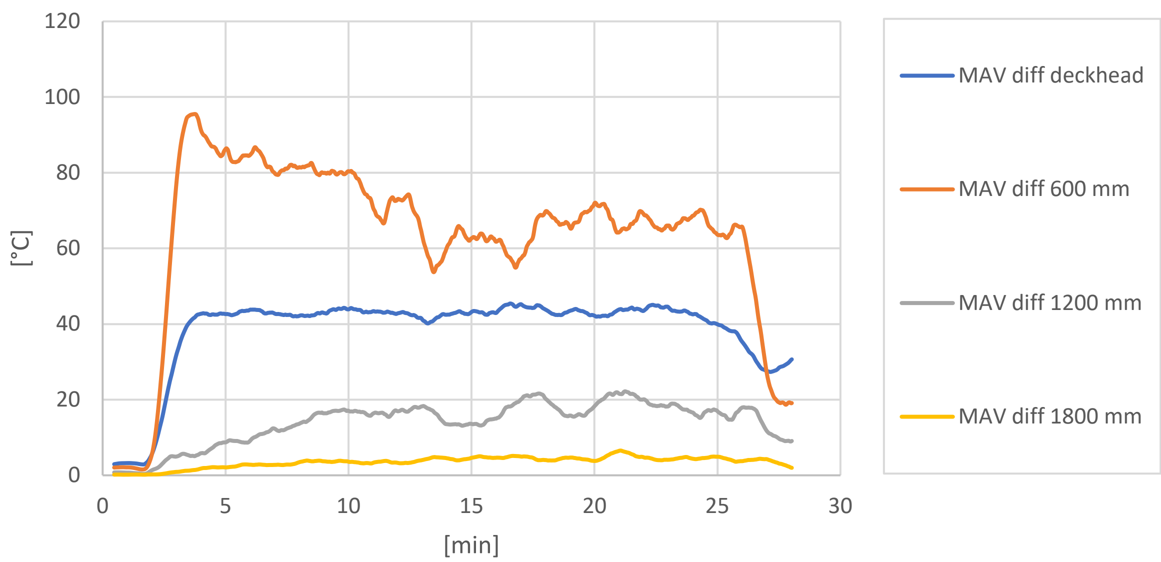

Figure 44. Test scenario 4. The moving average of the temperature difference across the fire curtains at the various height levels. First test, 2022-09-20.

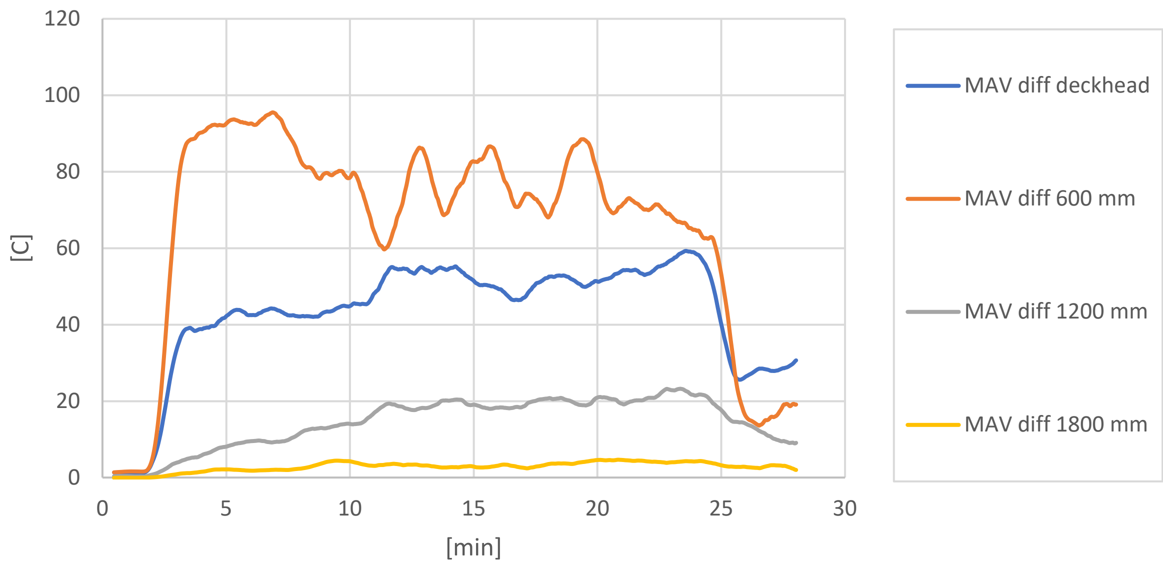

Figure 45. Test scenario 4. The moving average of the temperature difference across the fire curtains at the various height levels. Second test, 2022-09-21.

7.4.8.5 Test scenario 5. One van. Fire curtains down

In Figures A.25-A.32 in Annex A, are graphs which show the average of the thermocouples in each cross-sectional plane at different heights i.e. legend “Fire side curtain” is the average temperature of thermocouples C1, C25 and C13, legend “Cold side curtain” is the average of thermocouples C5, C29 and C17 and legend “Cold side” is the average of thermocouples C9, C33 and C21.

In Figures 21-22 the moving average, from the first and second test respectively (using a 1-minute window), of the temperature difference across the fire curtains i.e. the triad of thermocouples at each side of the fire curtain, at the various height levels are shown.

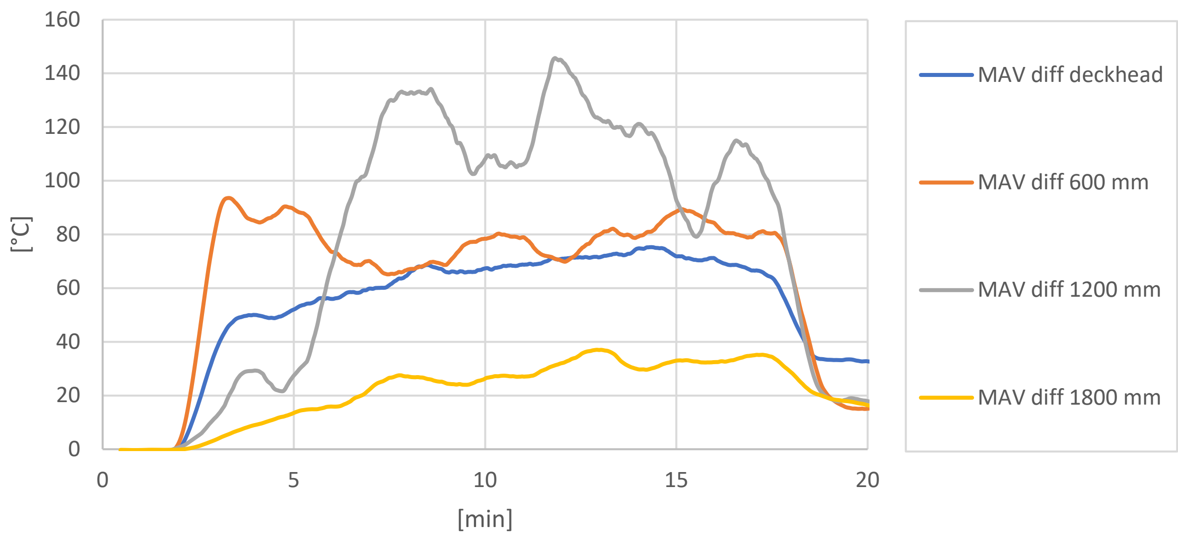

Figure 46. Test scenario 5. The moving average of the temperature difference across the fire curtains at the various height levels. First test, 2022-09-21.

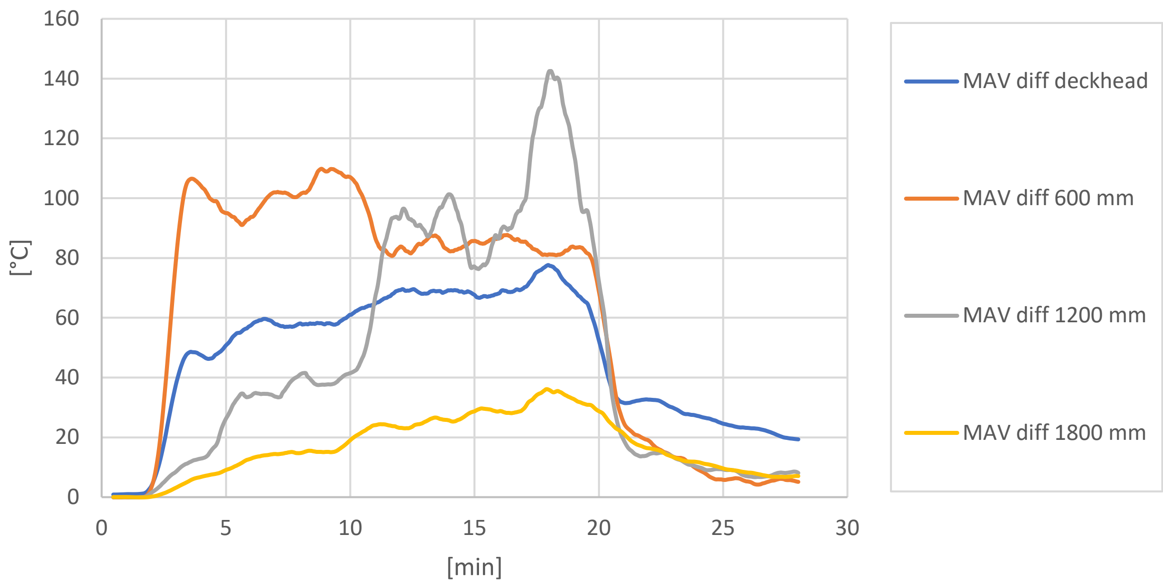

Figure 47. Test scenario 5. The moving average of the temperature difference across the fire curtains at the various height levels. Second test, 2022-09-22.

7.4.9 Discussion on large scale tests

Test scenario 1. No vehicles. Fire curtains up

Since the curtains are completely up the temperature differences in the container space are similar. The temperature difference across the curtain is negligible, around 35°C. This scenario serves as a reference scenario.

Test scenario 2. No vehicles. Fire curtains down

When the fire curtains are rolled down a difference in temperature across the fire curtain is more noticeable than in the reference scenario, around 160°C, particularly 600 mm down from the deckhead. This is probably due to the temperature of the deckhead. The thermocouple positioned 600 mm down is within the smoke layer which is obstructed by the fire curtain.

Test scenario 3. One passenger car. Fire curtains down

When a passenger car is present in one of the lanes, the fire curtains will cover less of the cross-sectional area. Consequently, the temperature difference in the smoke layer across the fire curtain decreases, around 100-120°C. Both tests using this scenario show the same trend.

Test scenario 4. One passenger car, one van. Fire curtains down

When both a passenger car and a van is present in the lanes the cross-sectional area is further reduced. Thus, decreasing the temperature difference, around 60-80°C, in the smoke layer across the fire curtain. Both tests using this scenario show the same trend.

Test scenario 5. One van. Fire curtains down

Both tests in this scenario had different wind conditions compared to the other tests, specifically a hard wind which made the fuel source burn quicker and at a higher temperature due to oxygen entrainment. The main difference in results compared to the other scenarios is that it is the thermocouples at position 1200 mm down from the bulkhead that shows the most difference in temperature across the fire curtain. The difference is about the same as in test scenario 4 (60-80°C) but occurs at a lower height. It is probably due to a thicker smoke layer.

7.4.10 Summary of the observations from the large-scale tests with fabric curtain

The tested fabric was withstanding 50 kW/m^2 for 50 minutes without sustainable visible flame in a cone calorimeter test. No fire spread was measured during large scale set up.

Based on the experiments performed with fabric curtain, it is seen that the curtain influences the temperature propagation within the confined space. In the experiments it is probably the smoke layer that dictates the temperature. The smoke layer is a function of the pool fire and the geometry of the space and the openings (ventilation) and thus will the result vary depending on fire and geometry. It can be concluded that if the curtain obstructs the smoke layer, the temperature propagation is hindered within the confined space. The loading conditions and fire scenario on board a ro-ro space will play a role in the efficiency for containment of a rolled down smoke curtain.

Photos which illustrate the smoke layer from both sides of the curtain is shown in Figure 48.

Figure 48. Photos from test scenario 3. Left photo: the “cold side”. Right and middle photo: the fire side.

From the pictures it can be seen that the curtain is not blocking the smoke to pass from one side to the other, when the curtain is partly rolled down.

Regarding the ability to pass a rolled down curtain it can be concluded that it took as long time to walk through the container with the rolled down curtain, as it took without rolled down curtain. In both scenarios, the time to move from one short end of the space to the other was approximately 10 seconds. The walk was made with fully equipped firefighting gear.

7.5 Cost assessment – Fabric curtain concepts

Main author of the chapter: Vito Radolovic, FLOW

Investment, operation, maintenance, and end of life costs for a solution with fabric curtain installed on board are further assessed in this section. The cost assessment was made for newbuilding’s only. Two concepts are included for cost assessment:

- Solid curtain, transversal mounting, fully rolled down
- Striped curtain, transversal mounting, fully/partly rolled down

The cost assessment was made for reference ships selected by the project with respect to the applicability of the solutions proposed; Magnolia Seaways the generic ro-ro cargo ship operated by DFDS Seaways, and Stena Flavia, the generic ro-pax ship. The purchasing costs was estimated based on figures from system component suppliers. The estimated cost provided for the production, installation, and commissioning is based on a Croatian shipyard standard where the average cost per weight or length was estimated. Production and installation of steel structures is estimated, 2.5 EUR/t and 1.5 EUR/t, respectively. A cabling installation cost of 25 EUR/m was assumed.

It needs to be emphasized that the installation and operational cost is dependent on the ro-ro space arrangement for all solutions. Specifically, cargo space size (area) and deck structural arrangement have a considerable impact. Further, significant cost differences may occur depending on the business area i.e., shipyard location, particularly the installation cost.

7.5.1 Investment cost

The following items are considered:

- The purchasing cost for solid curtain system (curtain cassette and sewing, el. equipment, power, and signal cables)
- Additional construction steel (reduced web height)
- The labour cost for the engineering
- The labour cost for the installation work as well commissioning:
    - Installation of solid curtain system
    - installation of cabling
    - additional production and installation cost of steel structure(deck)

For newbuilding's no additional cost was assumed for documentation, certification, and other administration activities.

The purchasing costs was estimated based on figures from system component suppliers. The estimated cost provided for the production, installation, and commissioning is based on a Croatian shipyard standard where the average cost per weight or length was estimated. Production and installation of steel structures is estimated, 2.5 EUR/t and 1.5 EUR/t, respectively. A cabling installation cost of 25 EUR/m was assumed.

The estimated cost for the installation of the fabric curtain on a ro-pax and a ro-ro cargo is summarized in Table 10.

Table 10. Investment cost for striped and solid curtain, transversal mounting

	Striped curtain		**Solid curtain**	
Investment costs [EUR]:	**Ro-pax**	**Ro-ro cargo**	**Ro-pax**	**Ro-ro cargo**
Purchase	328 440	434 240	193 200	275 200
Insurance	-	-	-	-
Integration design and validation	3000	3000	3000	3000
Road transporter	-	-	-	-
Ship transporter	-	-	-	-
Assembly/installation	98 310	97 250	49 560	47 250
Commissioning	3000	3000	3000	3000
Documentation, certification, and other administrational	-	-	-	-
Loss of hire	-	-	-	-
Operator training	-	-	-	-

Other	-	-	-	-
Total investment cost [EUR]	**432 750**	**537 490**	**248 760**	**328 450**

7.5.2 Operation cost

The following items are considered:

- Additional crew operation during stowage (movable decks only)
- Additional crew operation at movable ramps (flaps, etc.)
- Loss of revenue

Influence on the operational cost by adding additional weight of the added system and steel weight is considered negligible.

Loss of revenue cost is considered only for movable decks at generic ro-ro cargo ship, where a break in the cargo stowage is assumed.

Loss of revenue cost is based on the Stena and DFDS fleet statistics, where the average loss of revenue per lane meter of 8000 EUR/LM for ro-ro cargo is estimated. Further, average loss in cargo area i.e., in lane meters of 2 meters for stowage on movable decks is estimated at each solid curtain. A total of 40 lane meters loss for ro-ro cargo is considered. Further, it is assumed that movable decks are used on 25% of the voyages.

The operational cost for the installation of fabric curtain on a ro-pax and a ro-ro cargo is considered and summarized in Table 11. Note that for ro-pax newbuilding's the solutions it is assumed that the impact on the operational cost is negligible and therefore not considered (marked -).

Table 11. Operation cost for striped and solid curtain, transversal mounting.

	Striped curtain		**Solid curtain**	
Operation costs:	**Ro-pax**	**Ro-ro cargo**	**Ro-pax**	**Ro-ro cargo**
Additional energy consumption [kWh/year]	-	-	-	-
Additional fuel consumption [t/year]	-	-	-	-
Reduce fuel consumption [t/year]	-	-	-	-
Operator cost [EUR/year]	-	2000	4000	5000
Insurance, axes, and other fees [EUR/year]	-	-	-	-
Loss of cargo/loss of revenue [EUR/year]	-	80 000	1 152 000	1 968 000
Additional of cargo/profit revenue [EUR/year]	-	-	-	-
Other [EUR/year]	-	-	-	-
Total operation cost [EUR/year]	**-**	**82 000**	**1 156 000**	**1 973 000**

7.5.3 Maintenance cost

Maintenance cost estimation is based on figures received from suppliers. The estimated cost for inspections, testing, and maintenance for the four system solutions on a ro-pax and a ro-ro cargo newbuilding is summarized in Table 12.

Table 12. Maintenance cost for striped and solid curtain, transversal mounting

	Striped curtain		Solid curtain	
Maintenance costs [EUR/year]:	**Ro-pax**	**Ro-ro cargo**	**Ro-pax**	**Ro-ro cargo**
Annual system maintenance	6000	6000	2000	2000
Loss due to vessel downtime during maintenance	-	-	-	-
Other maintenance cost	-	-	-	-
Total operation cost [EUR/year]	**6000**	**6000**	**2000**	**2000**

7.5.4 End-of-life cost
No end-of-life cost considered.

7.6 Summary regarding fabric curtain solution
Main author of the chapter: Anna Olofsson, RISE

Means for vertical subdivision of ro-ro spaces by using fabric curtains were first evaluated in the reduced-scale tests. These tests showed that smoke spread may be stopped, and radiant heat completely blocked, provided that the curtains extend vertically all the way down to the deck. In the reduced scale tests, fabric curtains used together with water mist curtains were able to significantly reduce the HRR of the fire in case the openings of the ro-ro space were closed. Large-scale experiments were performed with a striped curtain solution, to allow the curtain to better adapt to the height of the cargo depending on the loading conditions. It can be concluded that if the curtain is lower than the height of the smoke layer, temperature propagation is at large limited to the area confined by the curtain. The largest difference in temperature between the side with the fire and the side with no fire was achieved with a curtain rolled down all the way to the deck.

The onboard demonstrations concluded challenges with mounting a fabric curtain in the deckhead on existing ships, due to e.g., existing equipment and the layout of girders in the deckhead. Existing vessels were therefore excluded from a fabric curtain solution and only newbuildings were considered when assessing installation design aspects and in the cost assessment. The striped curtain solution causes manageable structural modifications for newbuildings but hardly manageable modifications for ro-ro spaces with movable decks. For movable decks this will lead to an increased complexity of the deck arrangement, cargo loading/unloading operation and loss of revenue. The solid curtains can feasibly be arranged to follow the drencher zones where and divide each ro-ro space in two parts, additionally close the forward and aft opening of open ro-ro spaces towards the weather deck, where applicable.

The cost assessment generated general lower costs for investment and operation on ro-pax ships compared to ro-ro cargo ships. The striped curtain solution had a higher cost for investment and lower costs for operation, compared to the solid curtain. Maintenance was considered the same for both types of ships, with lower costs for the solid curtain. It needs to be emphasized that the installation and operational costs are dependent on the ro-ro space arrangement for fabric curtain solutions. Specifically, cargo space size (area) and deck structural arrangement have a considerable impact. It is difficult to scale the cost per ship type, lane meters, or deck area, where the cost must be calculated on a case-by-case basis. Further, significant cost differences may occur depending on the geographical business area, e.g. shipyard location, particularly the installation cost.

To sum up, every ro-ro space is different and there may certainly be ro-ro spaces where a fabric curtain fits and is easier to install than in other ro-ro spaces. What drives costs is mainly loss of cargo rather than the investment and maintenance. Depending on the height of the smoke layer vs. height of cargo, the curtain can be more or less effective in regard to fire safety.

8 Conclusion

Main author of the chapter: Anna Olofsson, RISE

The conducted studies have assessed the development for vertical subdivision of ro-ro spaces by considering smoke, fire, and heat integrity as well as regulatory, integration and cost aspects. It contributes to the objective to develop and demonstrate means for subdivision of ro-ro spaces.

Two different types of subdivisions were developed and evaluated: water curtain and fabric curtain. Both water and fabric curtain solutions have potential to containment but shows challenges in terms of installation and costs, and the fact that there are no guidelines regulating water or fabric curtain design and performance currently available for ships. If curtains are to be implemented in ro-ro spaces, standards and test protocols need to be developed. Based on the present study and discussions with the advisory groups in the LASH FIRE project, the solid fabric curtain solution is chosen prior to a water curtain as subdivision of ro-ro space. None of the solutions was chosen to proceed to the part of cost-effectiveness assessment. Specific conclusions for water and fabric curtain are presented below.

8.1 Conclusion on the water curtain solution

Main authors of the chapter: Pascal Boulet, LUL and Antti Virkajarvi, MAR

Experiments were done for various operating conditions: type and size of fire, use of one or two water curtains, closed or opened side openings, presence of blocks representing the cargo. The system showed relevant performances regarding heat (radiation in particular) containment. Smoke containment was also obtained, at least partially, but some drawbacks were observed, and the system performances are questionable regarding this criterion.

Water mist is undoubtedly a powerful solution for fire suppression and control. However, some weaknesses inherent to the present application were identified during the reduced scale study, namely smoke destratification, turbulent mixing promoting some fire increase in some cases, smoke flow through the water curtain after its activation, increase of the smoke exhaust at the side openings within the space. At this stage the use of water mist seems to induce a cost increase for a benefit which is still questionable within the present application.

Moreover, the recommendations which should be done to apply the system would raise important difficulties to the ship operators, with a loss of space for a partial containment (regarding smoke propagation) and potential problems of smoke exhaust enhanced through the side openings.

8.2 Conclusion on the fabric curtain solution

Main author of the chapter: Anna Olofsson, RISE

Both reduced- and large-scale tests show that a curtain that is fully rolled down results in effective subdivision of a ro-ro space in term of shielding of hot smoke. A partly rolled down curtain has the advantage that it does not reduce the cargo loading space, but it is not as effective subdivider as a solid curtain. The project proposes a solid curtain to subdivide a ro-ro space is the most rational solution, and to install it following drencher zone boundary. For ship integration purposes, this solution is found feasible only for newbuildings, for ro-pax ships and ro-ro cargo ships. To roll down the curtain, a free space in a straight line across the width of the deck is needed, which requires cargo separation and hence implies loss of cargo/revenue. This is the main cost driver and makes it reasonable to only install one subdivider per ro-ro space, or two subdividers if the ro-ro space is very large (e.g. including more than 4 drencher zones). However, no cost-effectiveness assessment has been carried out to justify this fire safety measure in LASH FIRE.

9 References

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10 Indexes

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11 ANNEXES

11.1 ANNEX A - Results from large scale test with fabric curtain

Main authors of the chapter: Kim Olsson, Magnus Bobert, Örjan Westlund, RISE

11.1.1 Test scenario 1

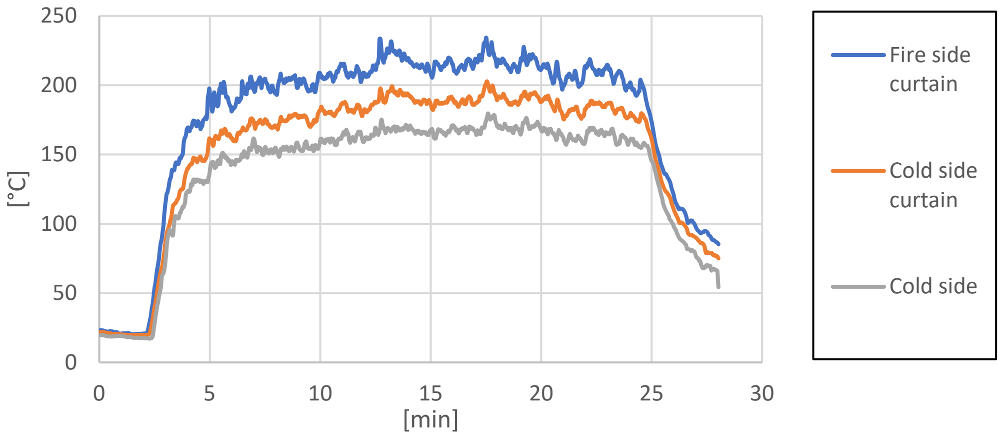

Figure A.1. Test scenario 1. Temperatures closest to deckhead.

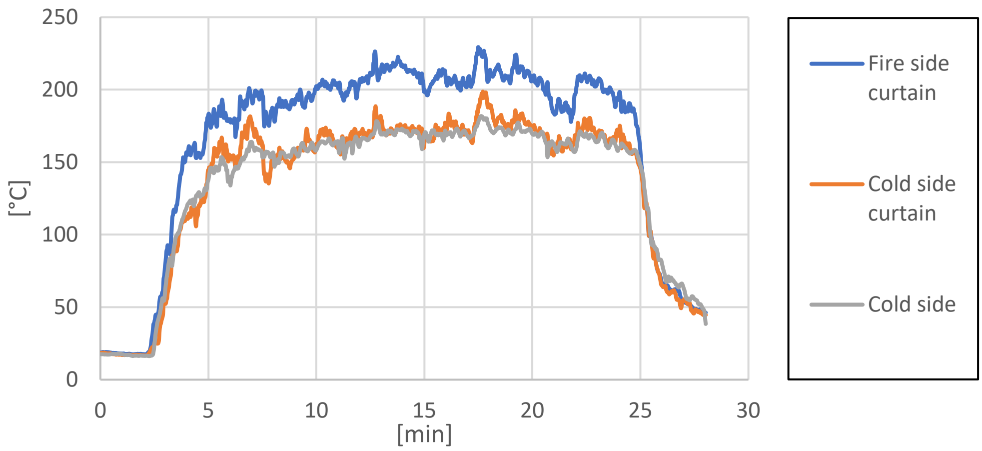

Figure A.2. Test scenario 1. Temperatures 600 mm from deckhead.

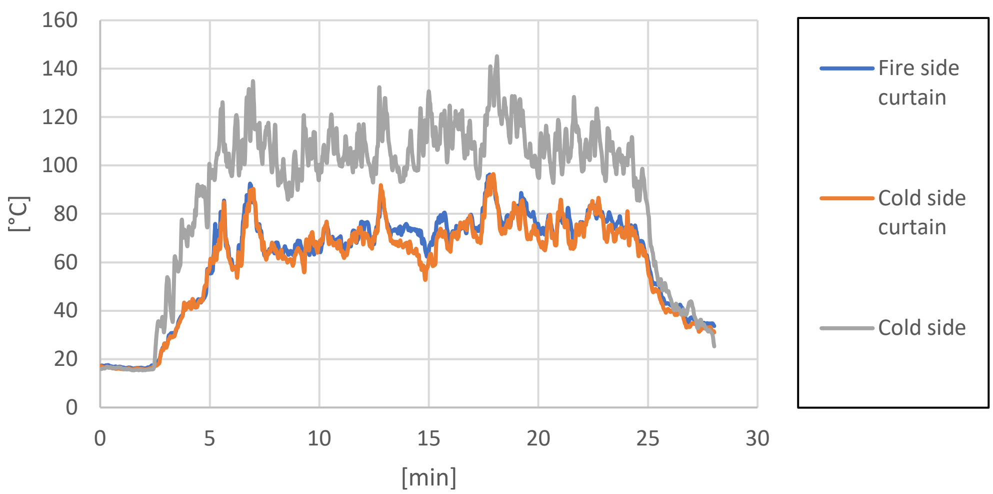

Figure A.3. Test scenario 1. Temperatures 1200 mm from deckhead.

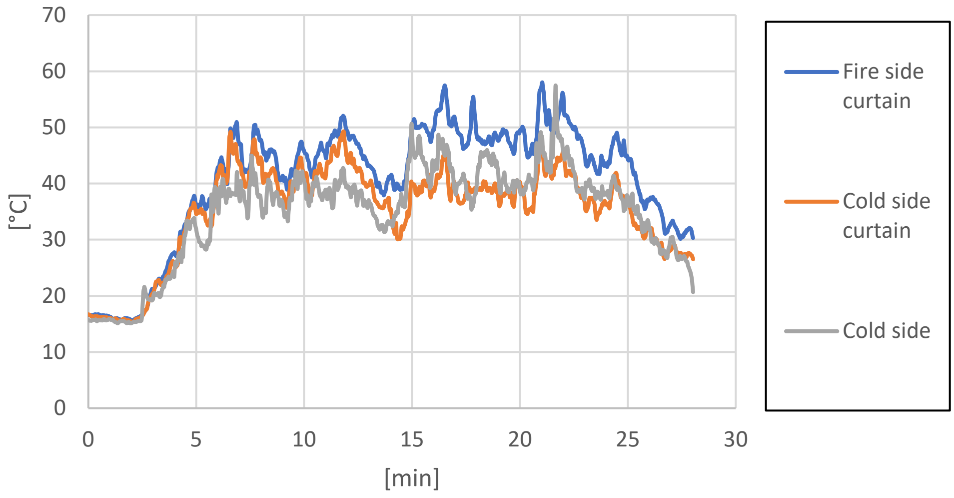

Figure A.4. Test scenario 1. Temperatures 1800 mm from deckhead.

11.1.2 Test scenario 2

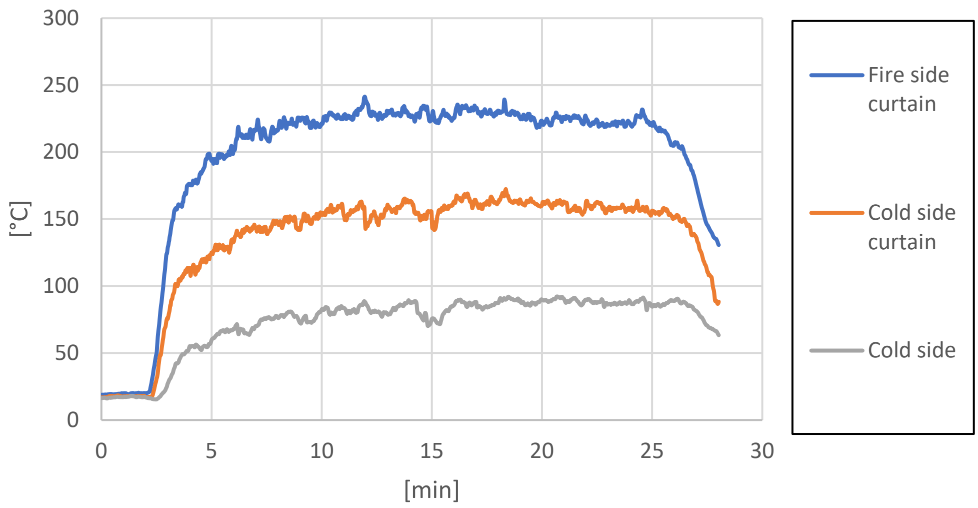

Figure A.5. Test scenario 2. Temperatures closest to deckhead.

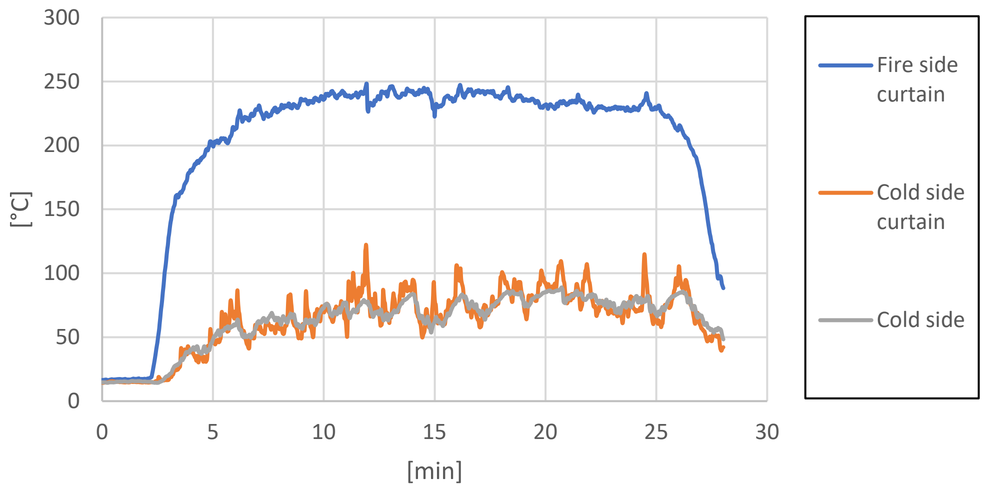

Figure A.6. Test scenario 2. Temperatures 600 mm from deckhead.

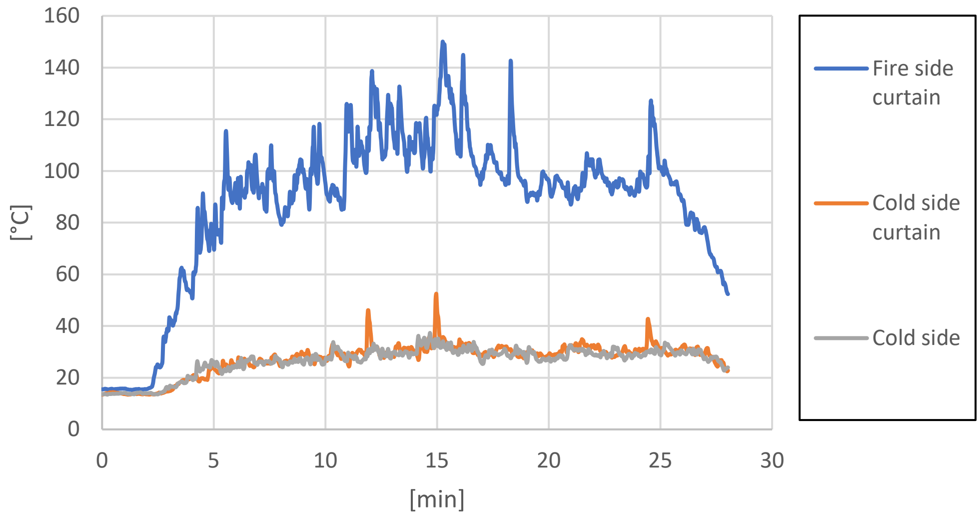

Figure A.7. Test scenario 2. Temperatures 1200 mm from deckhead.

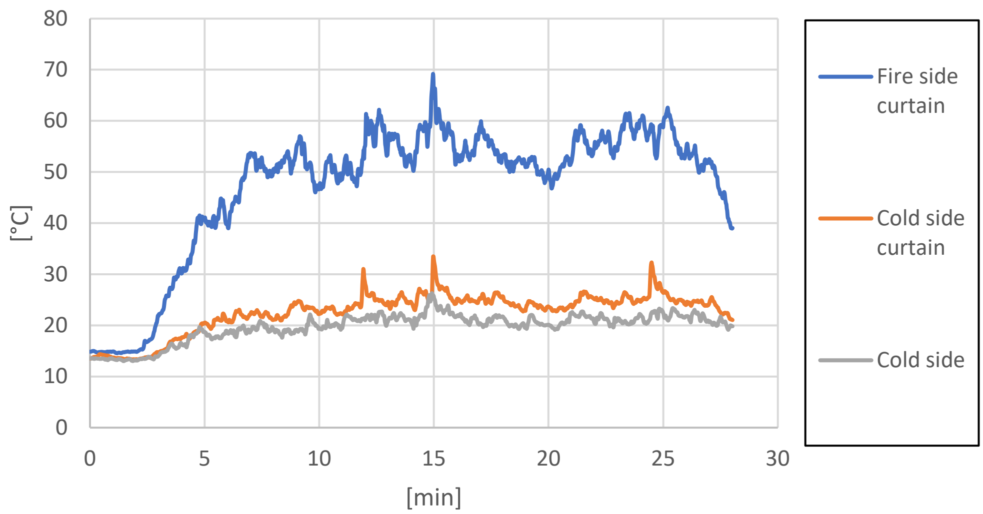

Figure A.8. Test scenario 2. Temperatures 1800 mm from deckhead.

11.1.3 Test scenario 3

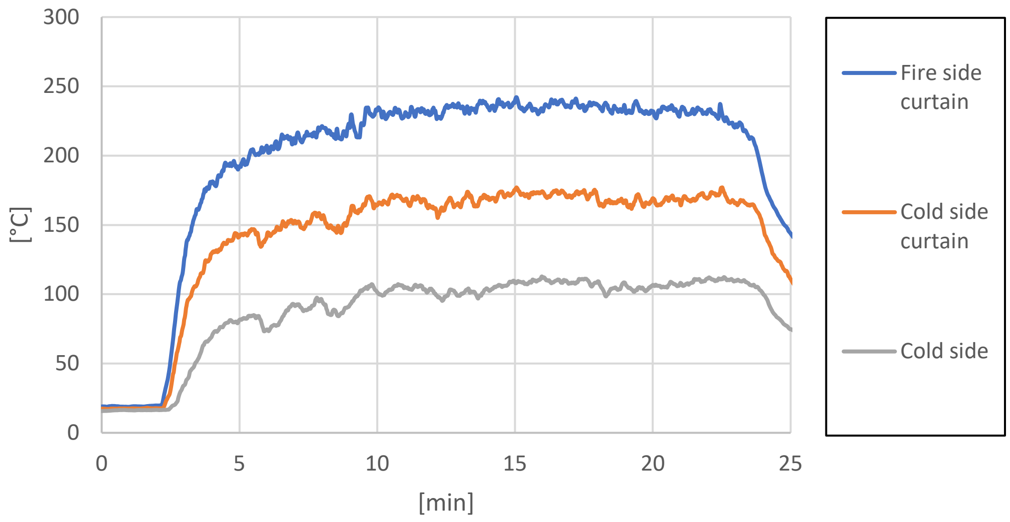

Figure A.9. Test scenario 3. First test 2022-09-19. Temperatures closest to deckhead.

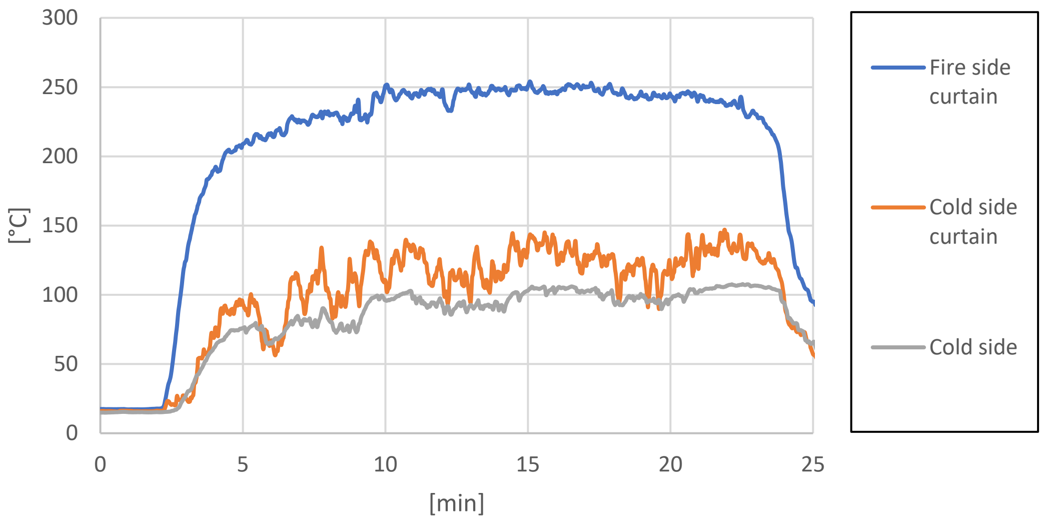

Figure A.10. Test scenario 3. First test 2022-09-19. Temperatures 600 mm from deckhead.

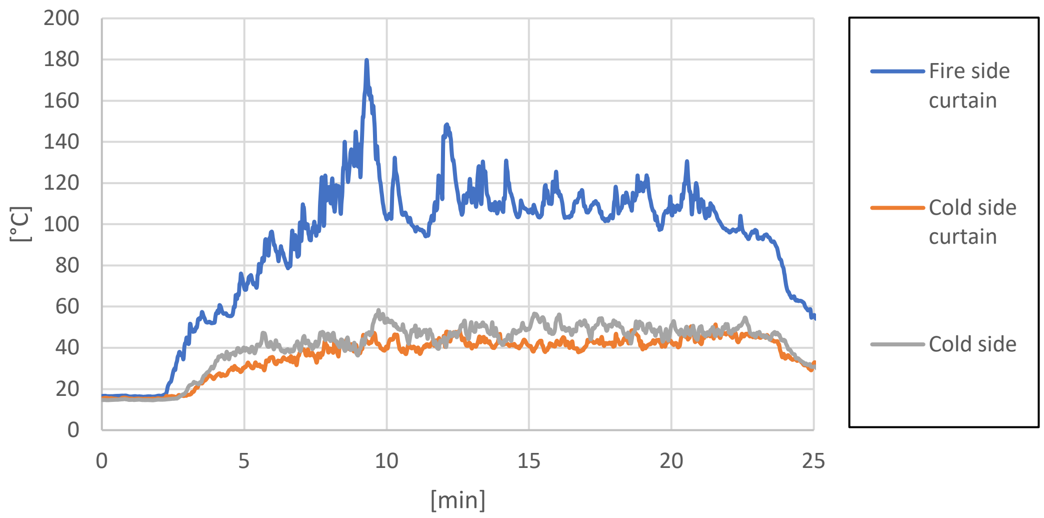

Figure A.11. Test scenario 3. First test 2022-09-19. Temperatures 1200 mm from deckhead.

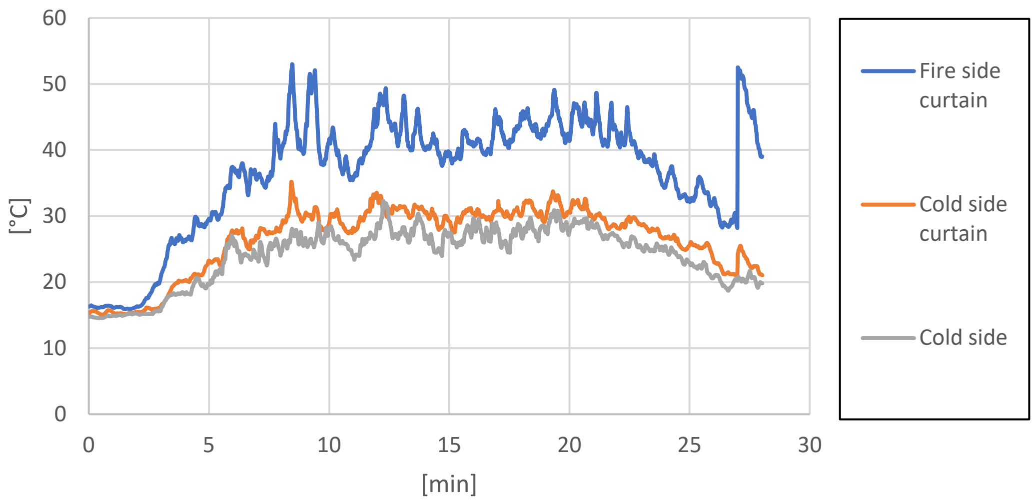

Figure A.12. Test scenario 3. First test 2022-09-19. Temperatures 1800 mm from deckhead.

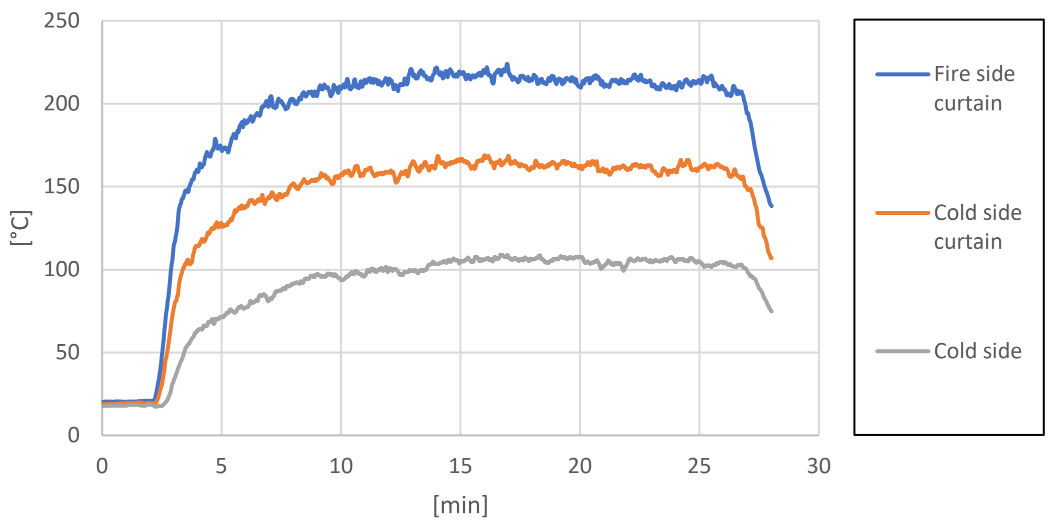

Figure A.13. Test scenario 3. Second test 2022-09-20. Temperatures closest to deckhead.

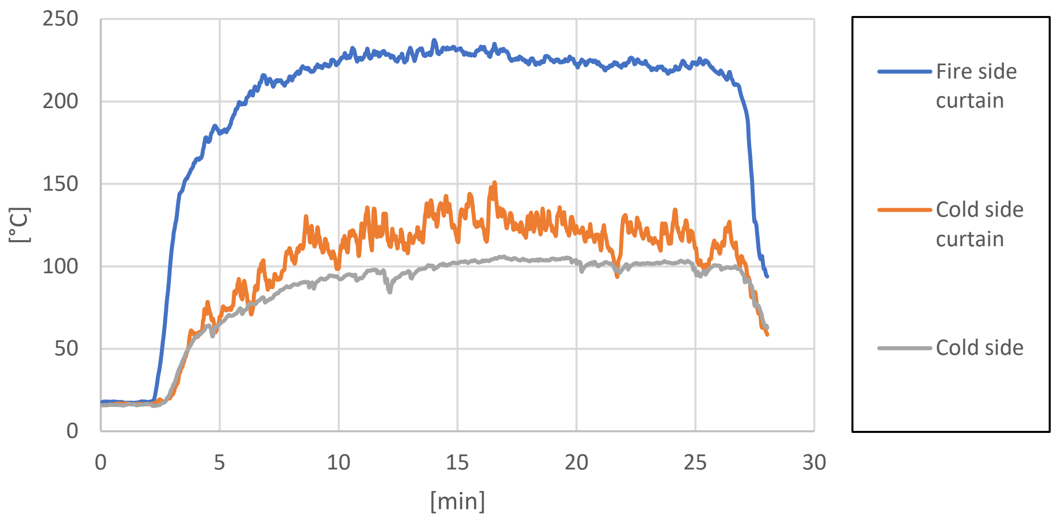

Figure A.14. Test scenario 3. Second test 2022-09-20. Temperatures 600 mm from deckhead.

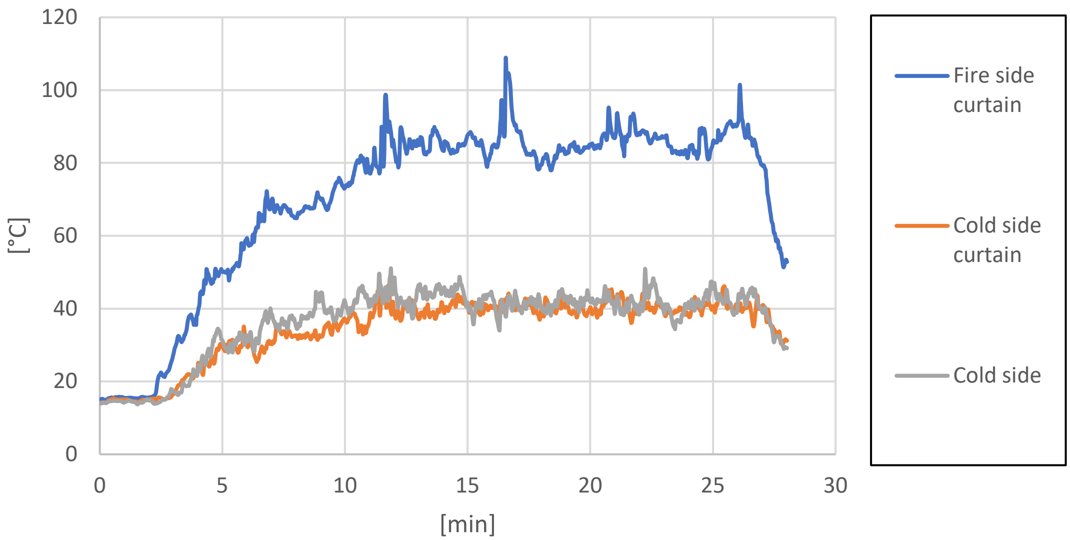

Figure A.15. Test scenario 3. Second test 2022-09-20. Temperatures 1200 mm from deckhead.

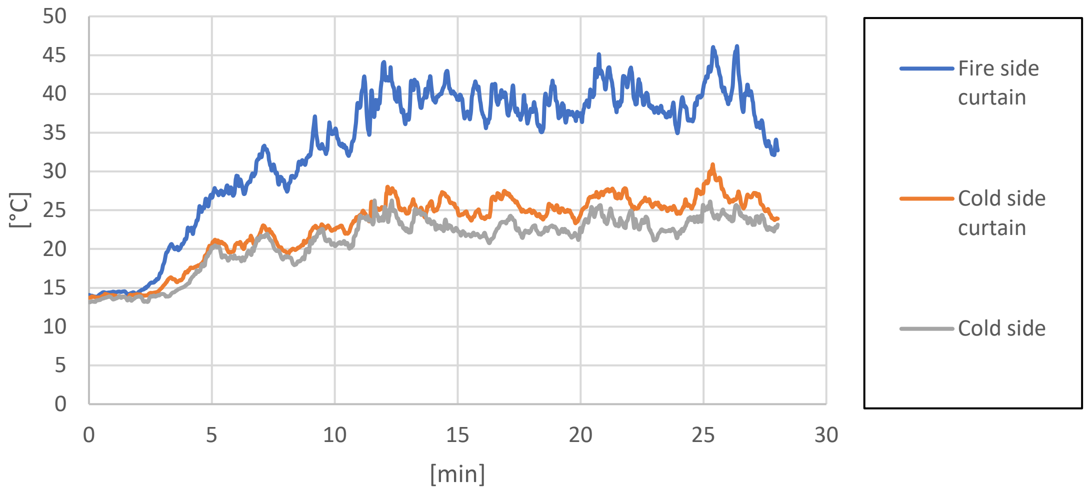

Figure A.16. Test scenario 3. Second test 2022-09-20. Temperatures 1800 mm from deckhead.

11.1.4 Test scenario 4

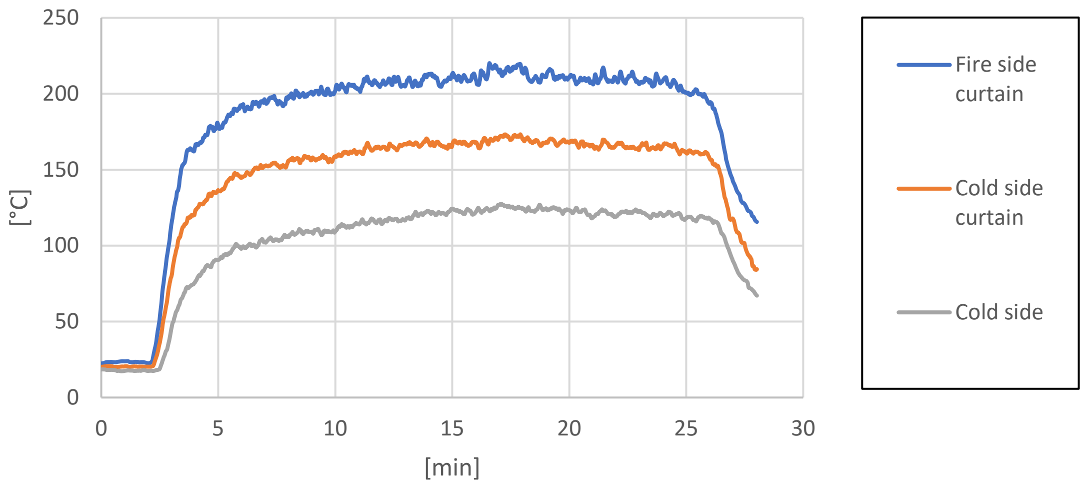

Figure A.17. Test scenario 4. First test 2022-09-20. Temperatures closest to deckhead.

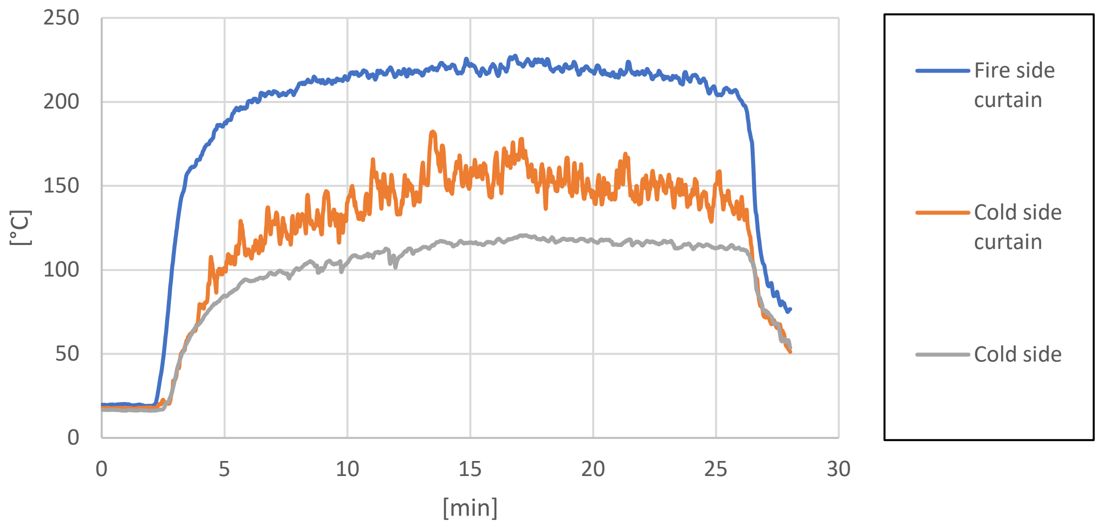

Figure A.18. Test scenario 4. First test 2022-09-20. Temperatures 600 mm from deckhead.

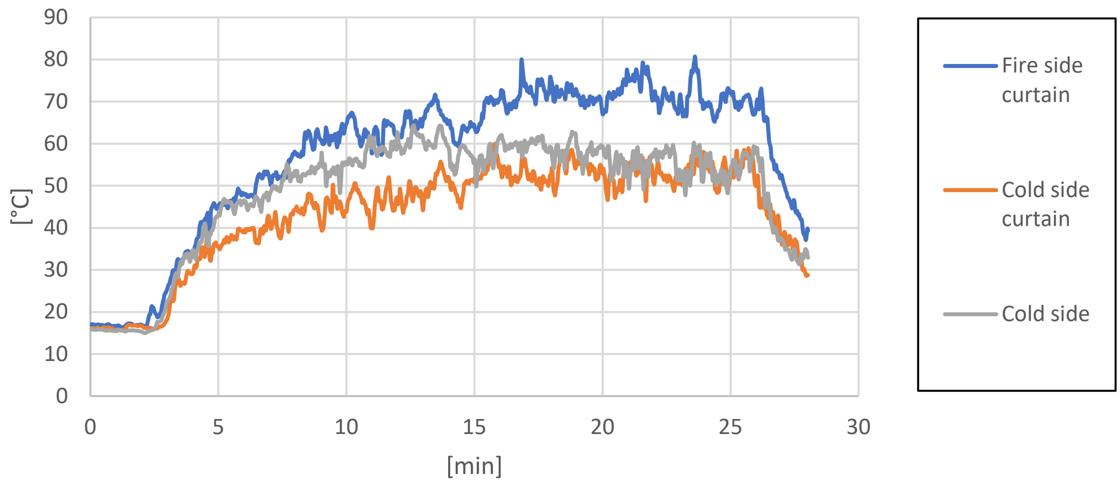

Figure A.19. Test scenario 4. First test 2022-09-20. Temperatures 1200 mm from deckhead.

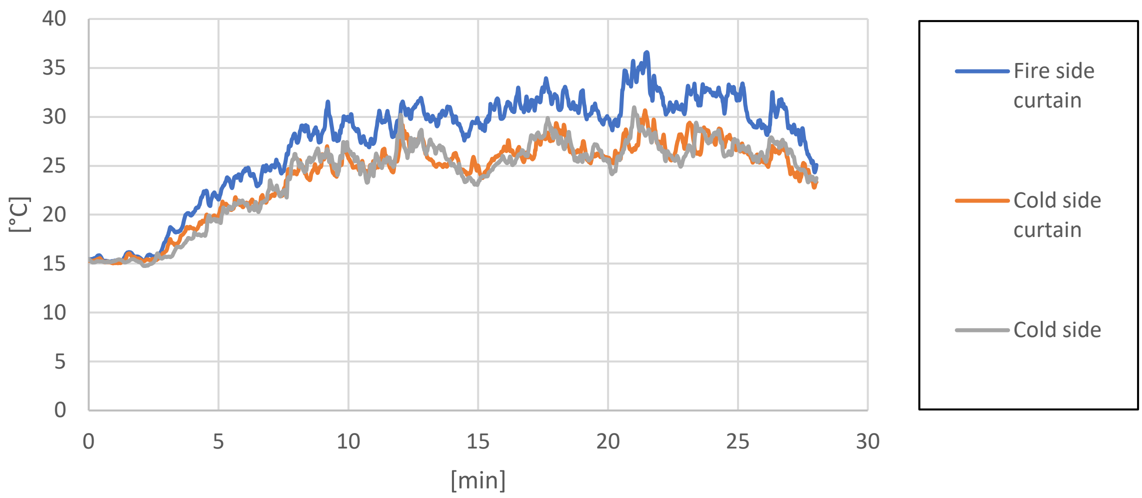

Figure A.20. Test scenario 4. First test 2022-09-20. Temperatures 1800 mm from deckhead.

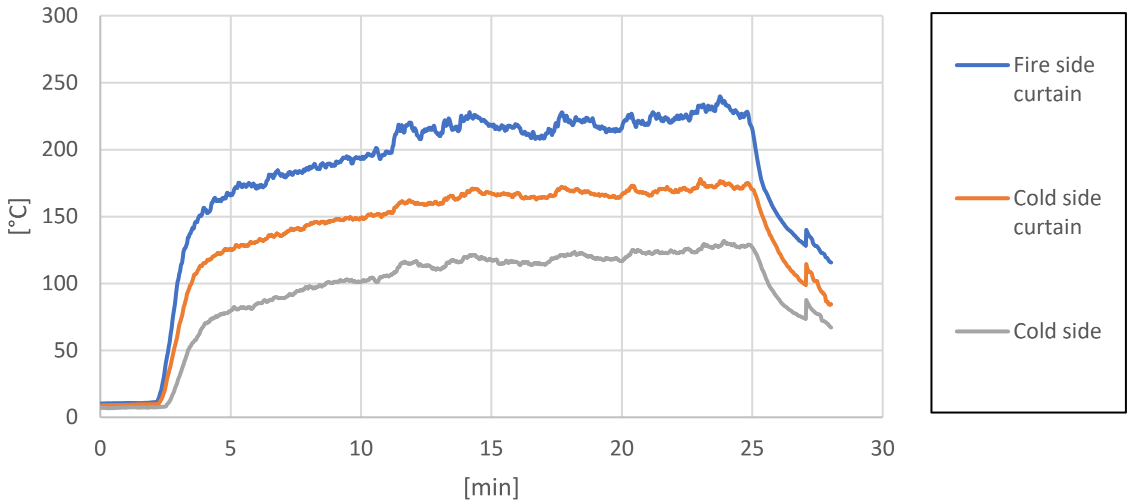

Figure A.21. Test scenario 4. Second test 2022-09-21. Temperatures closest to deckhead.

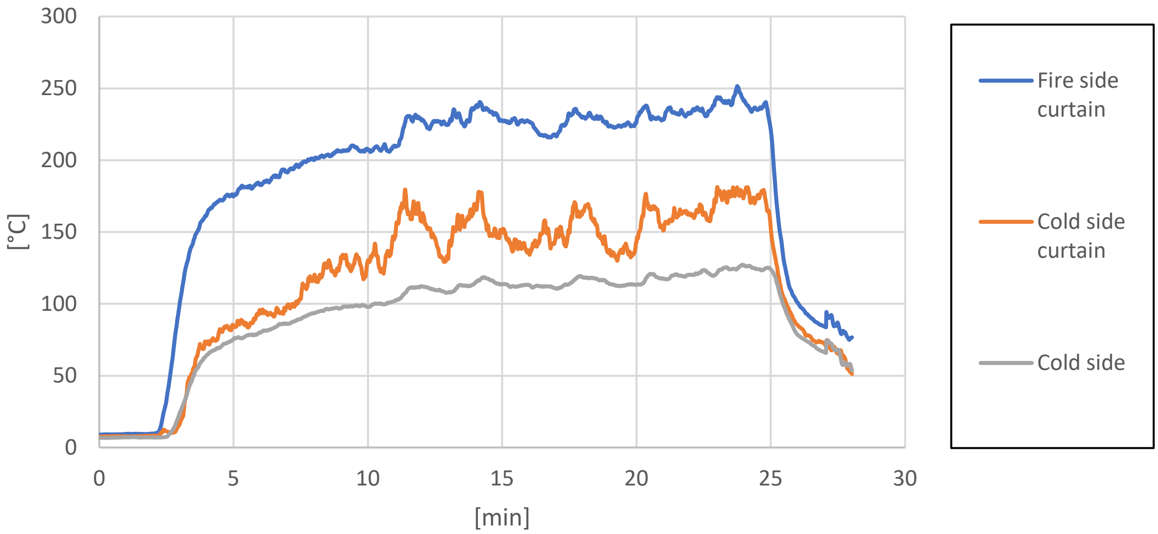

Figure A.22. Test scenario 4. Second test 2022-09-21. Temperatures 600 mm from deckhead.

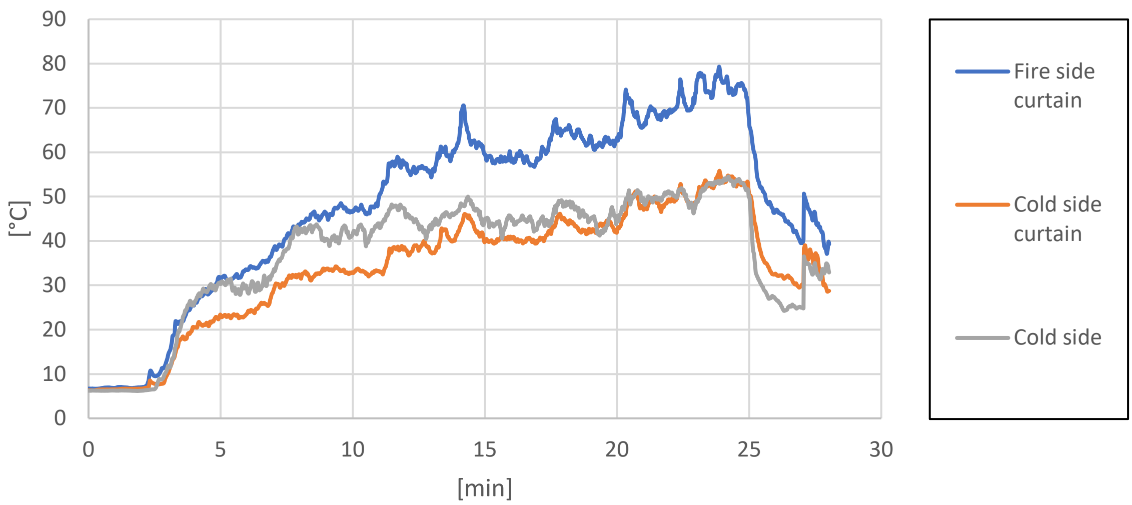

Figure A.23. Test scenario 4. Second test 2022-09-21. Temperatures 1200 mm from deckhead.

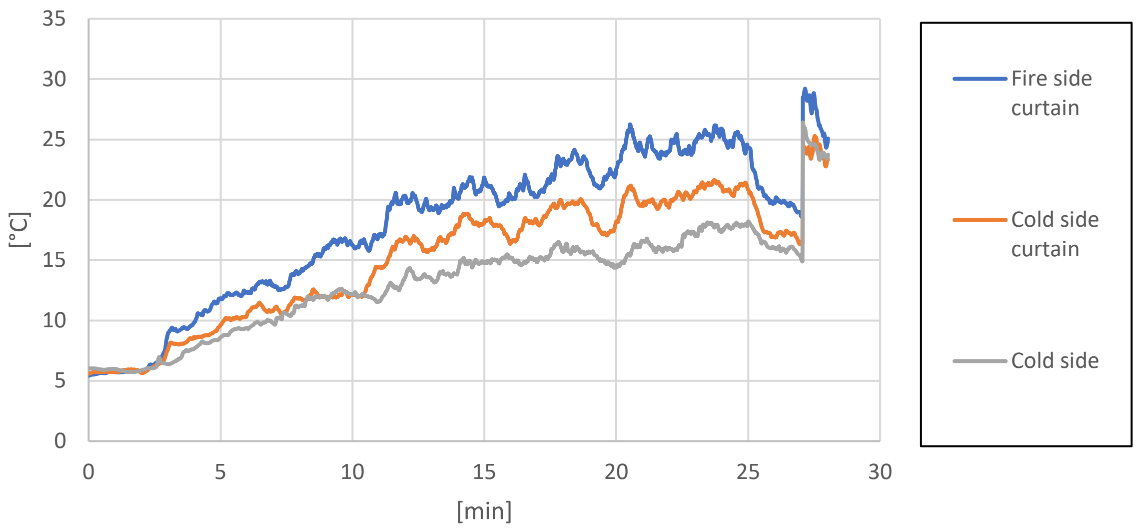

Figure A.24. Test scenario 4. Second test 2022-09-21. Temperatures 1800 mm from deckhead.

11.1.5 Test scenario 5

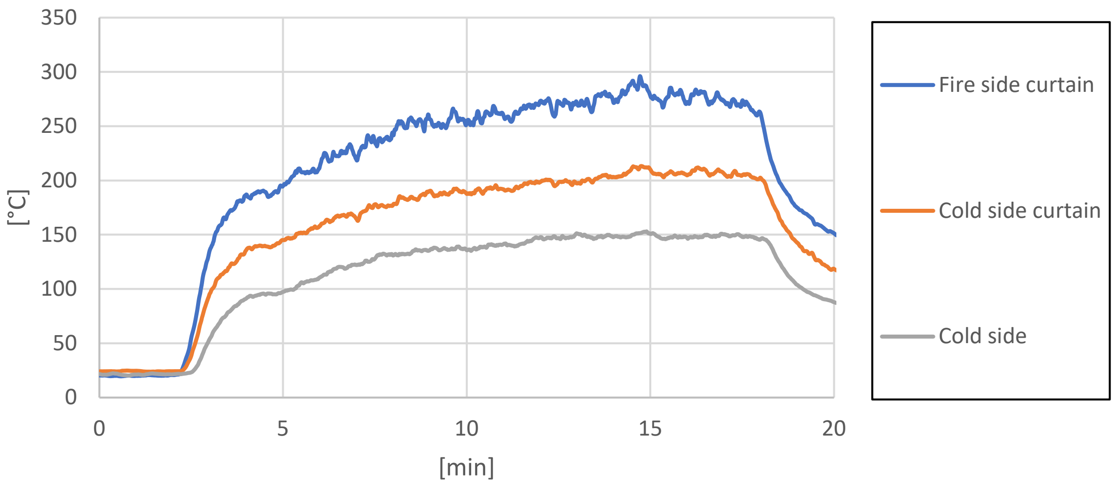

Figure A.25. Test scenario 5. First test 2022-09-21. Temperatures closest to deckhead.

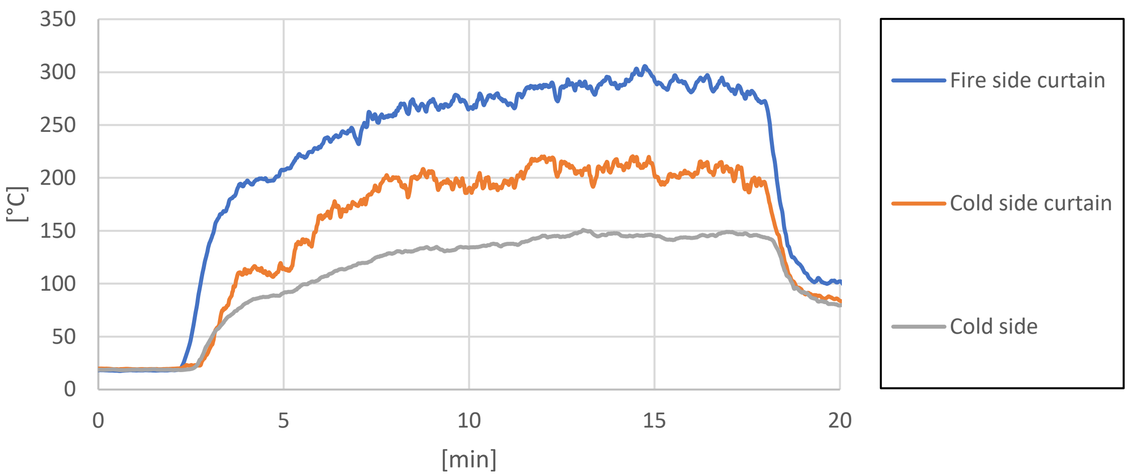

Figure A.26. Test scenario 5. First test 2022-09-21. Temperatures 600 mm from deckhead.

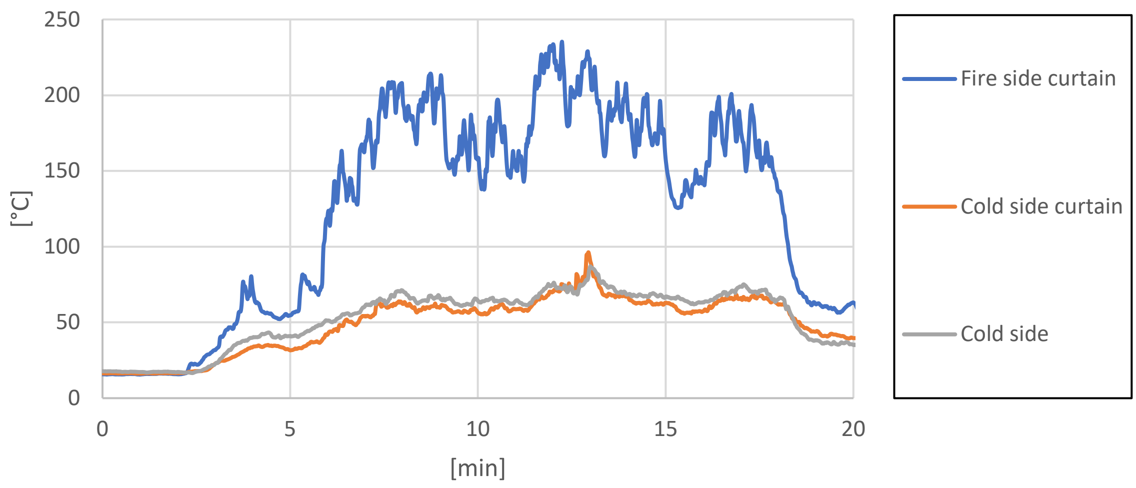

Figure A.27. Test scenario 5. First test 2022-09-21. Temperatures 1200 mm from deckhead.

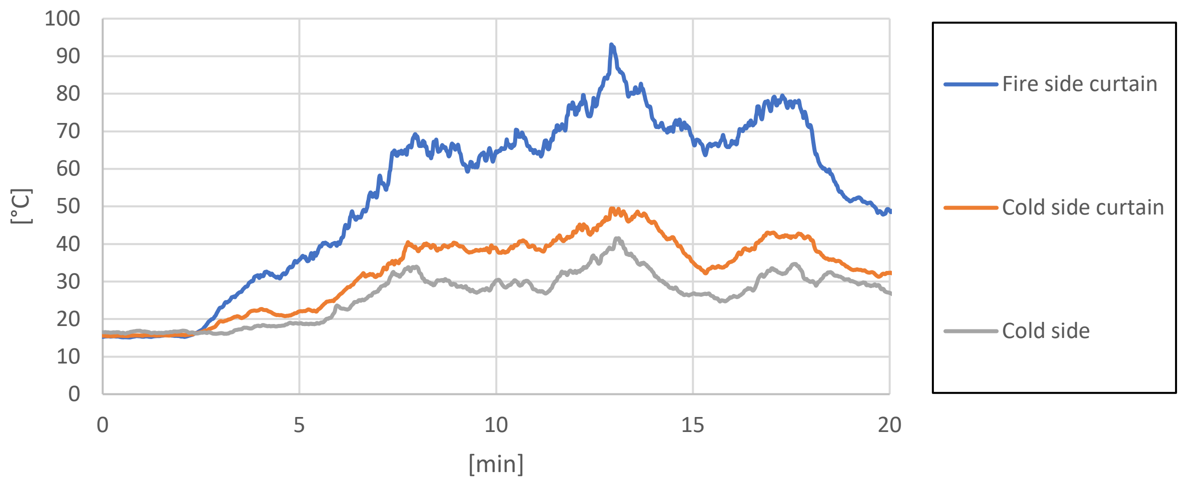

Figure A.28. Test scenario 5. First test 2022-09-21. Temperatures 1800 mm from deckhead.

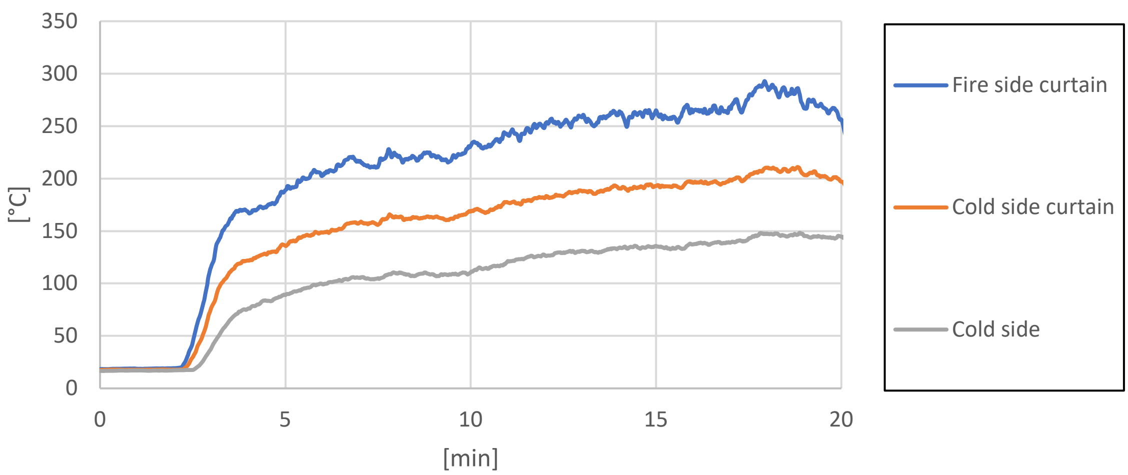

Figure A.29. Test scenario 5. Second test 2022-09-22. Temperatures closest to deckhead.

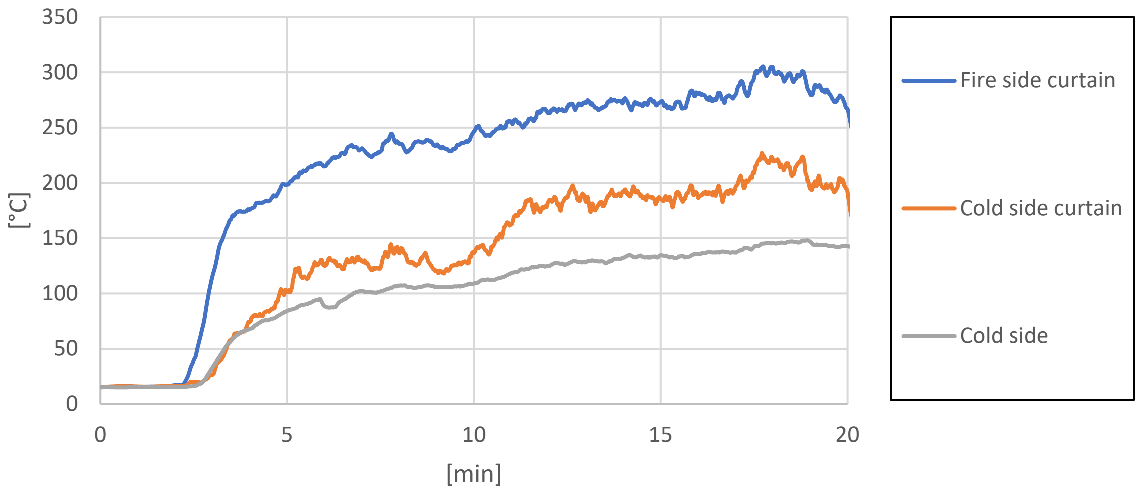

Figure A.30. Test scenario 5. Second test 2022-09-22. Temperatures 600 mm from deckhead.

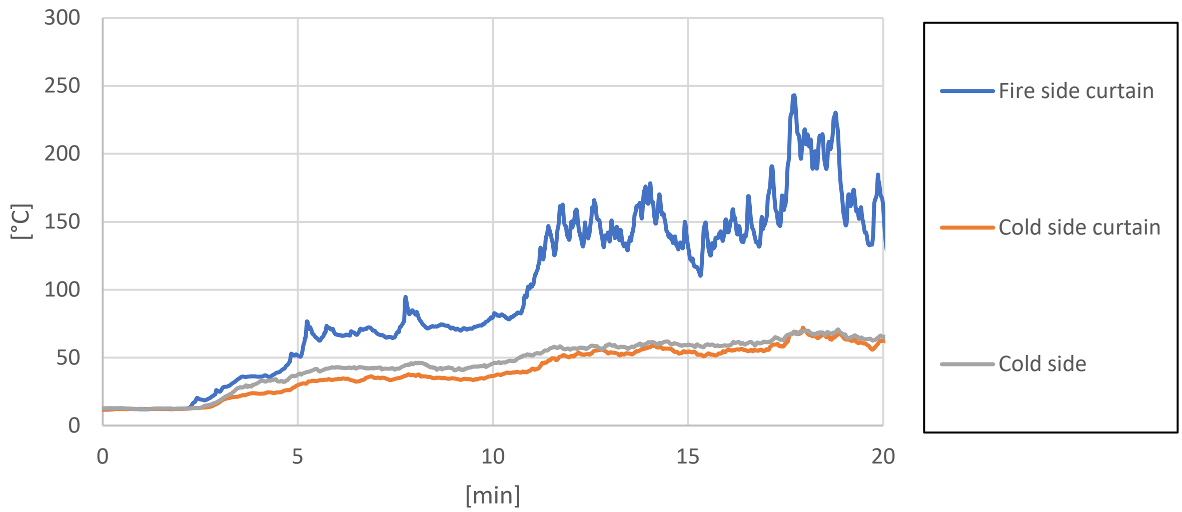

Figure A.31. Test scenario 5. Second test 2022-09-22. Temperatures 1200 mm from deckhead.

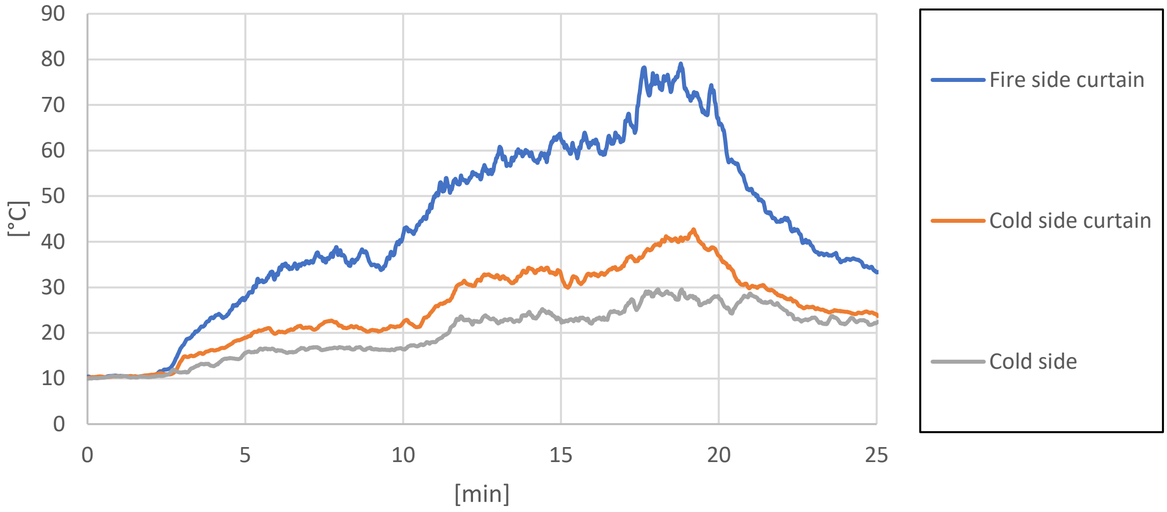

Figure A.32. Test scenario 5. Second test 2022-09-22. Temperatures 1800 mm from deckhead.

11.2 ANNEX B – Challenges with installing a fabric curtain in a ro-ro space

Main author of the chapter: David Schmidt, RISE

This annex illustrates some of the challenges noted during this project with regards to install a fabric curtain as subdivision for ro-ro spaces. Pictures from visits on board different ro-ro ships are shown.

11.2.1 Ramps, pillars etc.

Ramps are common in ro-ro spaces. Ramps and pillars need to be taking into account designing, mounting, and installing the system. See Figure 49.

Figure 49. Ramp and pillar on Magnolia Seaways.

11.2.2 Hoistable, moveable decks

Another challenge for the mounting of curtains is the hoistable decks and tween decks, see Figure 50.

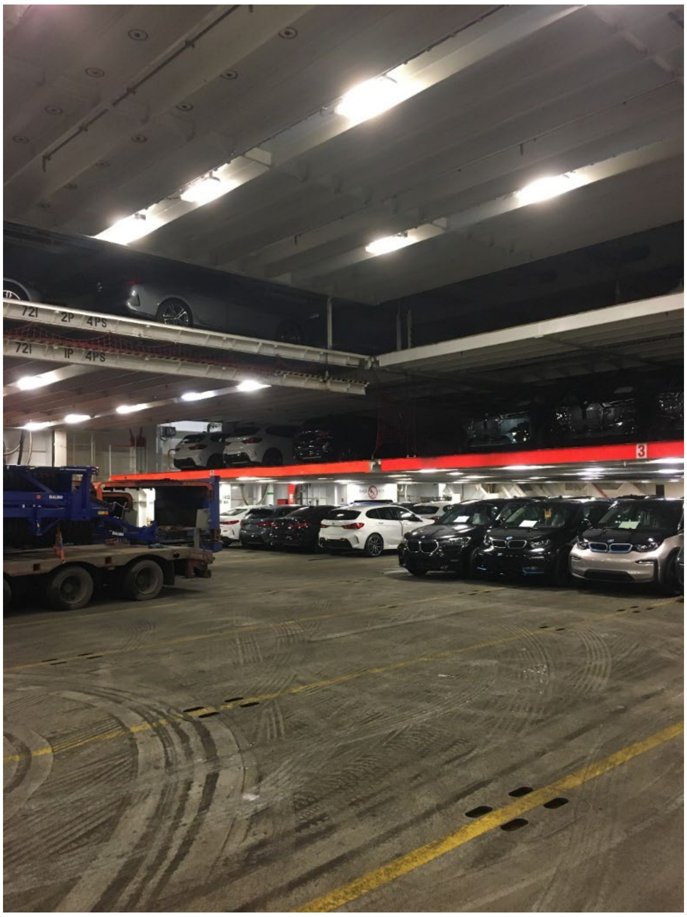

Figure 50. Tween decks on Magnolia Seaways

11.2.3 Equipment in deckhead

Mounted equipment in deckhead in a closed ro-ro space where girders, pipes sprinkler, lighting and cable trays would need to be considered in the mounting and installation phase. See Figure 51.

Figure 51. Roof mounted equipment on Stena Jutlandica

Example of routing of main pipes across the open ro-ro space longitudinal direction, this can interfere with mounting of fabric curtain. See Figure 52.

Figure 52. Hollandia Seaways piping at ceiling that can interfere with mounting of a fabric curtain.

Example of drencher zone marking for open ro-ro space longitudinal and transversal beams in combination and deckhead mounted equipment is shown in Figure 53. Compartments are isolated for fire integrity.

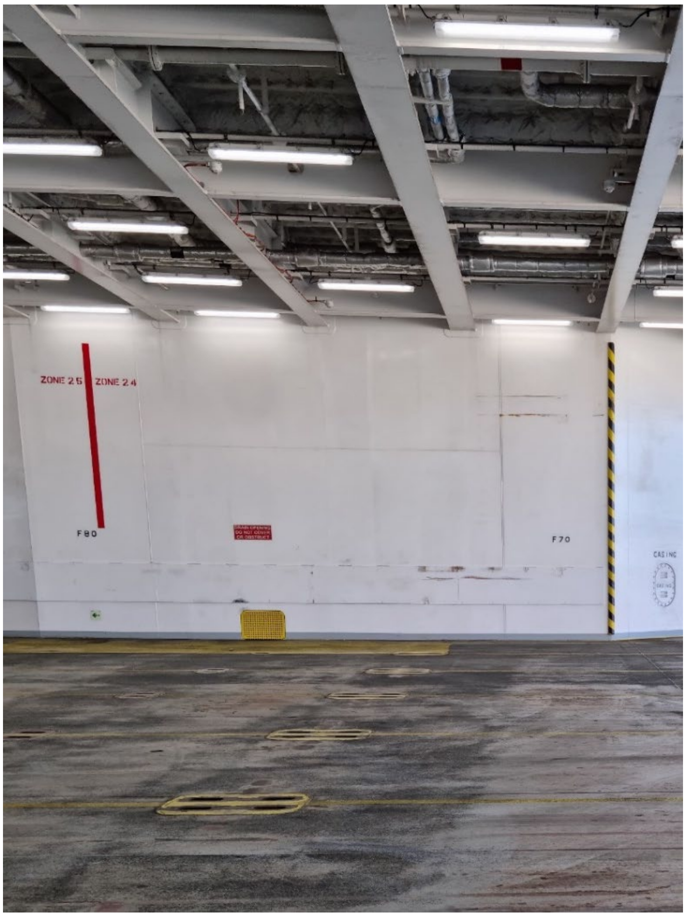

Figure 53. Drencher zone marking on Hollandia seaways

11.2.4 Expected gaps and hinder

Raised sidewalk at sides would aggravate the roll out all the way to deck, although a curtain for the full width would bend and expect to seal in in the middle due to the weight of curtain and steel bar but gaps are expected close to the sidewalks. See Figure 54. Note also the red clear markings of drencher zones across the deck.

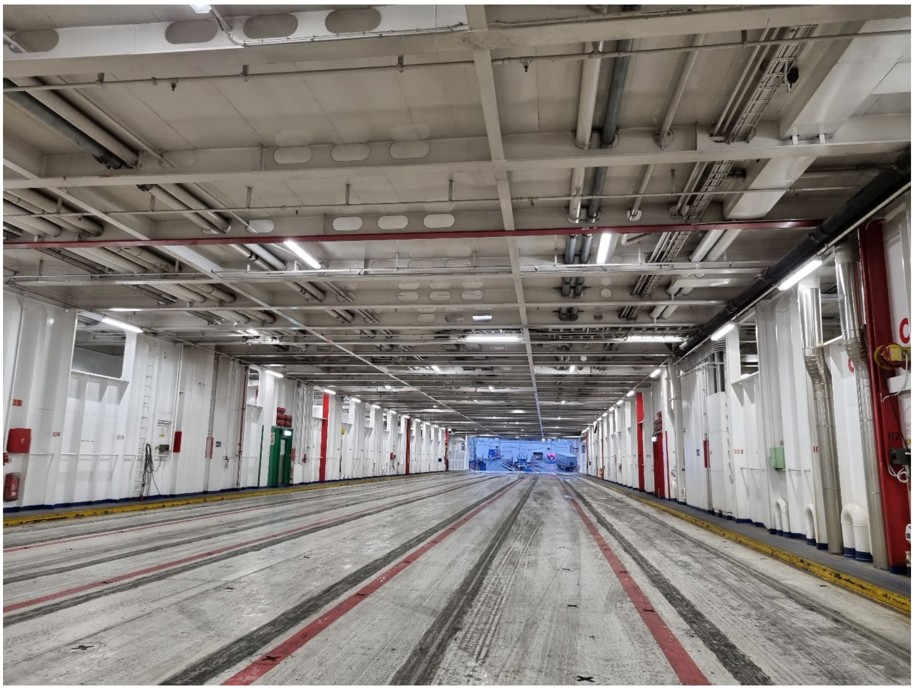

Figure 54. Raised sidewalks on Stena Jutlandica.

Example from an open ro-ro space is shown in Figure 55. A curtain would conflict with ramps at the sides, railing would hinder the curtain to drop all the way down. Note also beams both transversal and longitudinal at ceiling.

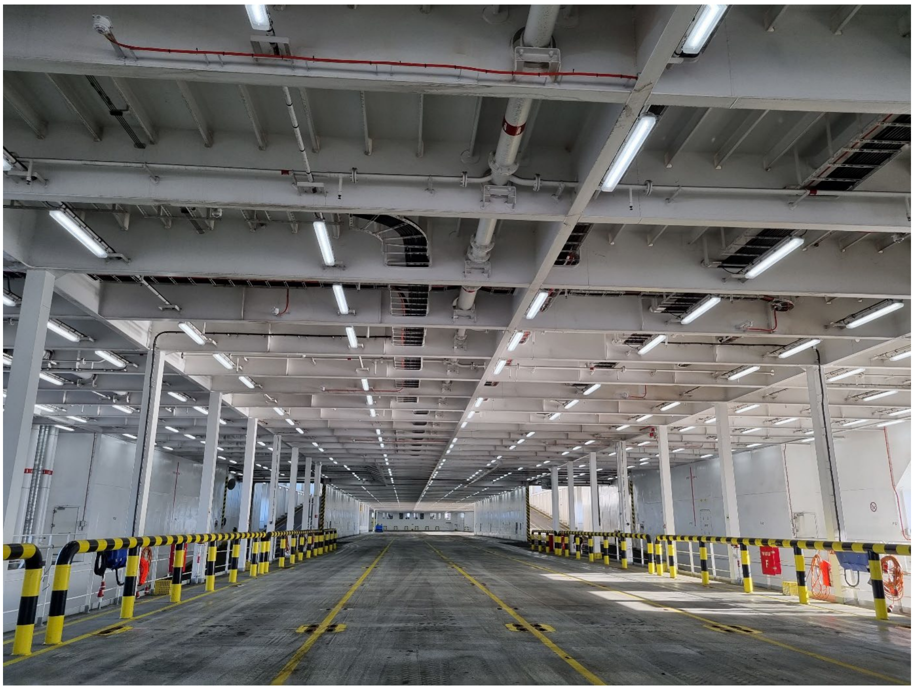

Figure 55. Example of a ro-ro space on Humbria Seaways.