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Elucidation and guidelines for ro-ro space ventilation in case of fire

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Abstract

A ro-ro space is regulated to be adequately ventilated (SOLAS II-2/20.1.3), either by permanent openings providing natural ventilation or by mechanical ventilation. The different requirements on ventilation depend on the type of ro-ro space, which is either an open ro-ro space, a closed ro-ro space or a weather deck. Open ro-ro spaces and weather deck have natural ventilation requirements while closed ro-ro spaces need mechanical ventilation. Different design solutions, e.g., location of permanent openings, number of fans, and duct locations, are seen onboard and each ro-ro space has a unique design of its ventilation to fulfil the requirement.

The work presented in this report is focused to explain how ventilation affects a fire in an open or a closed ro-ro space and to contribute to strengthen the independent fire protection of ro-ro ships. The result contributes to the LASH FIRE project objective 1. Risk control measures such as changed configuration of permanent openings and reversible fans was studied. Field studies, computer simulations, model scale tests, interaction with ship operator and crew has been conducted as part of the work for understanding how natural ventilation affect fire development and the development of a guideline to increase the knowledge of usage of mechanical ventilation in case of a fire in a ro-ro space.

Using mechanical ventilation can decrease smoke density in the ro-ro space, hence assist manual firefighting before drencher is activated. The first public version of the developed guideline is presented in ANNEX A - Guideline: Mechanical ventilation in case of fire in closed ro-ro spaces. Switching fans off is the praxis on board today and is the best alternative to reduce the fire intensity but generates worse visibility conditions in the space.

Regarding natural ventilation the work was not able to show that the side openings could be reduced below the required 10% and still maintain the same air exchange rate as the required 10 ACPH in a closed ro-ro space. Therefore, a reduced opening percentage in open ro-ro spaces is not deemed to be a feasible way forward for increased fire safety, without further investigations on air quality.

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Content

1 Executive summary

1.1 Problem definition

A ro-ro space is regulated to be adequately ventilated (SOLAS II-2/20.1.3), either by openings or by mechanical ventilation. The different requirements on ventilation depend on the type of ro-ro space, which is either an open ro-ro space, a closed ro-ro space or a weather deck. Open ro-ro spaces and weather deck have natural ventilation requirements while closed ro-ro spaces need mechanical ventilation. Different design solutions, e.g., location of permanent openings, number of fans, and duct locations, are seen onboard and each ro-ro space has a unique design of its ventilation to fulfil the requirement.

The work presented in this report is focused to study how ventilation affects a fire in an open and a closed ro-ro space and to contribute to strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current challenges of a fire.

1.2 Method

Two safety measures for ventilation were identified to study with computer simulations, the first relating to natural ventilation and the second relating to mechanical ventilation:

- [Natural ventilation] Changed configuration of side openings in open ro-ro spaces; and
- [Mechanical ventilation] SOLAS requirement of reversible fans (to facilitate manual interventions in closed ro-ro spaces).

Four items were formulated for the model scale tests, three for natural ventilation:

- Document the fire development (heat release rates (HRR), temperatures, and gases) in a reference scenario with 10% side openings located in the centre of the side plating (long walls) of the model, and with one end open.
- Determine the effects on the fire development when changing the opening configuration.
- Document how the opening distribution affects the fire development (heat release rates, temperatures, and gases).

For mechanical ventilation, the following mission was formulated:

- Document if and how fans could facilitate manual fire-fighting operations.

A guideline for how to manage mechanical ventilation in case of fire in a closed ro-ro space was developed based on the result and conclusions of the studies carried out and presented within this report. A reviewed version is presented in ANNEX A - Guideline: Mechanical ventilation in case of fire in closed ro-ro spaces.

1.3 Results and achievements

- Changed configuration of side openings:

The conducted study regarding natural ventilation shows that closing the permanent side openings affects the fire development and results in a less intense fire, i.e. a lower heat release rate (HRR). It also showed that keeping one short end open is enough to provide a single car fire with enough oxygen to not become ventilation controlled. The performed computer simulations were not able to show that the sides openings could be reduced below 10% and still maintain the same air exchange rate as 10 ACPH in a closed ro-ro space. Based on this, it was not deemed feasible to further look into decreasing the opening percentage in open ro-ro spaces. Lowering the openings while keeping the opening percentage to 10% will not reduce the fire development inside an open ro-ro space.

- Requirement of reversible fans:

Reversible fans are beneficial for having a possibility to change air flow direction depending on the fire location. If a fire is located close to an exhaust outlet, then keeping the fans on at increased capacity could decrease smoke density in the space compared to if a fire located in between a supply and exhaust, i.e., having the chance to reverse the fan is positive if it results in a fire located closer to the exhaust and extraction of gases. Visibility of 10 m can be achieved with 16 ACPH when fire is located in the proximity of an exhaust fan. The results indicate that mechanical ventilation could facilitate manual firefighting in the early phase of a fire in a closed ro-ro space. When a fire inside a closed ro-ro space exceeds 5 MW (1 car burning), the current praxis of shutting down the ventilation and activate the extinguishing system is not challenged. It should be noted that the effects on fire spread have not been included in this study.

- Development of guideline

The usage of mechanical ventilation is an active tool, which needs to be trained, adjusted to the specific fire scenario and to the ship specific ventilation conditions. The developed guideline can be seen as a first step of awareness for keeping fans on in case of fire (only studied for fires up to a single car and no fire development). Since both a fire scenario and the prevailing conditions are dynamic the study has not been able to cover all scenarios and conditions. It is up to each ship to familiarize with the guidelines and to practise and understand how and if mechanical ventilation in case of fire can be a tool on board their vessel.

1.4 Contribution to LASH FIRE objectives

The results in this report contribute to the LASH FIRE objective 1 to strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current and future challenges in all stages of a fire.

The results have determined effects of natural and mechanical ventilation on fire development and evaluated current possibilities and new measures for smoke containment and prepared a guideline for mechanical ventilation in case of fire in closed ro-ro space.

1.5 Exploitation

The result can be exploited by ship operators by using the developed guideline to understand ventilation effects for a fire scenario and to develop their own ship specific ventilation strategy for practise and by that be more prepared for an upcoming real fire event.

The work will be possible to be used for continuing research regarding ventilation concepts for ro-ro spaces and to continue the exploration and discussion regarding the openness of an open ro-ro space.

2 List of symbols and abbreviations

A-60	A-class division insulated for 60 minutes
ACPH	Air changes per hour
BD	Bi-directional
CFD	Computational fluid dynamics
Circ.	Circular issued by IMO following meetings of the MSC
CO	Carbon monoxide
CO_2	Carbon dioxide
DG	Dangerous goods
EMSA	European Maritime Safety Agency
FDS	Fire dynamic simulator
HRR	Heat release rate
IACS	International Association of Classification Societies
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
ISO	International Standardization Organization
kW	Kilowatt
LEL	Lower explosion limit
MJ	Megajoule
MMF	French Flag Administration
MSC	IMO Maritime Safety Committee
MW	Megawatt
N_2	Nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
O_2	Oxygen
PCTC	Pure Car/Truck Carrier
PT	Plate thermocouple
Ro-pax	Ro-ro passenger
Ro-ro	Roll on roll off
SOLAS	International Convention for the Safety of Life at Sea
UCSG CFR	United States Coast Guard Code of Federal Regulations
UK MCA	United Kingdom Flag Administration
WP	Work package

3 Introduction

Main author of the chapter: Anna Olofsson, RISE

A ro-ro space is regulated to be adequately ventilated (SOLAS II-2/20.1.3), either by openings or by mechanical ventilation. The different requirements on ventilation depend on the type of ro-ro space, which is either an open ro-ro space, a closed ro-ro space or a weather deck. Open ro-ro spaces and weather deck has natural ventilation requirements while closed ro-ro spaces need mechanical ventilation. Different design solutions, e.g., location of permanent openings, number of fans, and duct locations, are seen onboard and each ro-ro space has a unique design of its ventilation to fulfil the requirement.

Regarding fire safety, ventilation (natural or mechanical) is crucial to the growth, intensity and burning time of fires in ro-ro spaces but effects are not clear and measures for managing ventilation in case of fire are missing. The openings in an open ro-ro space can feed a fire with fresh air from the outside and the fire can go on for days if there are enough fuel [1]. Fuel is normally not a problem since the space is filled with vehicles with fuel in their tanks and other rolled on cargo. Deactivation of the fans and closing the fire dampers in the ventilation system is standard procedure in case of fire in a ro-ro space today. Critical spreading of smoke to accommodations, restaurant or evacuation routes can be a problem in case of fire.

The objective of work package 11 in LASH FIRE is to eliminate significant containment weaknesses, considering smoke, fire, and heat integrity. This is achieved by four actions with the following goals:

A. Develop and demonstrate artificial and new means for fire integrity sub-division of ro-ro spaces.
B. Develop solutions and recommendations to ensure safe evacuation (fire integrity for 3 hours) and when evacuating at foreign port.
C. Develop ro-ro space openings design guidelines by assessment of the risks of smoke and heat transfer from ro-ro space openings to life-saving appliances, adjacent areas, and ventilation inlets.
D. Determine the effects of natural and mechanical ventilation on fire development and evaluate current possibilities and new measures for smoke containment.

The work presented in this report is focused to Action 11-D and to contribute to strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current and future challenges of a fire.

Chapter 4 provide an outlook on state-of-the art ventilation in case of fire, and ventilation on board ro-ro ships. **Chapter 5** is a regulatory review concerning ro-ro space ventilation, this is followed by **Chapter 6** regarding requirements for ship integration. Then, **Chapter 7** is dedicated to method for the conducted simulations and fire tests, followed by **Chapter 8** with results for natural ventilation and **Chapter 9** for results on mechanical ventilation. **Chapter 10** provides the shorter story for the development of a guideline and **Chapter 11**. Finally, a discussion is provided in **Chapter 12**.

4 Outlook on ventilation

Main author of the chapter: Anna Olofsson, RISE

4.1 State-of-the-art

This chapter provides state-of-the-art on what is currently used in terms of fire ventilation in other domains and modern technology.

Fire ventilation is used in the land-based rescue service in Sweden and other countries as one measure in the event of a fire in a building. The book *Fire ventilation* [2] by Stefan Svensson, includes the basic theories and principles for fire ventilation, how fire gases spread in buildings and how gases find their way out of buildings. Svensson [2] indicate that *“It is simply difficult to exactly determine how fire ventilation should be implemented in every specific situation”* because it is based on different variables, e.g. the available resources, the building, and the fire behaviour. The book presents the basic principle of fire ventilation as *“to actively and in a controlled way change the conditions in a burning building with the intention of releasing heat or fire gases out of the building”.* And continue by listing some of the purposes of fire ventilation as follows:

- Facilitate evacuation from the building.
- Facilitate fire and rescue operations.
- Prevent or contain spread of fire/fire gases.
- Enable or facilitate salvage operations or overhaul activities at an early stage.

By using fire ventilation, and thereby change the conditions in the gas flow the impact of pressure, heat and gases will be reduced, and air will most probably flow into the building which can have unwanted consequences. However, for a fire in a building the experience is that fire ventilation rarely degrades the result of an operation provided that the ventilation measure is controlled and coordinated with other measures, e.g., suppression. The book is based on many years of knowledge. In the IMO Circular MSC.1/Circ.1515 [3] it is expressed that it is important to gain experience and be properly trained and familiarized with the system and procedures to be able to make a decision on how to use the ventilation.

In RO5 study [1], fire ventilation was introduced in the model scale testing series by increasing the ACPH for the exhaust ventilation. The conclusion from that study is that only increasing the air changes per hour (ACPH) for the exhaust ventilation is not solving the problem of decreasing the fire development in a ro-ro space. The opposite, to lower the ACPH is neither solving the problem of decreasing the fire development in a ro-ro space. Shutting down the ventilation, however, leads to a sharp decrease of temperature according to the tests and simulations performed in the RO5 [1].

Regarding underground systems including mines and tunnels during construction, a previous RISE study [4] summarizes that it is better to be restrictive with the supply of fresh air that can increase the fire and thereby increase the risk of fire growth and the spread of fire gases. Therefore, as a general rule, the recommendation in the report is to switch off the ventilation system when a fire is detected.

Portable fans are another tool used in land-based firefighting. For example, to pressurize a staircase in a high apartment building and thus keeping the stair free from fire gases and to prevent spread of fire and fire gases to the staircase [2]. It is also mentioned as a strategy to be used for tunnels with through-flow, to increase or affect the air flow [4].

Jet fans are seen in car parking garages and a jet fan system is used to force the air flow towards the exhaust fans and thus removing the contaminated air and smoke from the space. This way of pushing gases can also be called positive pressure ventilation and is described for buildings in [2]. Svensson is clear that this method does not fit all types of buildings. From the RO5 [1] it is shown in a simulation that jet fans can provide a smoke free area in a ro-ro space for the fire team to operate in, but the simulation did not have any output of the fire development. Two scenarios were simulated; one with the existing ventilation system and one with six jet fans added to the model from the first simulation. Jet fans are also found on board ro-ro vessels today, as part of the general ventilation system and not to be used in case of fire.

Air quality control systems is used in other domains, such as classrooms and offices where the ventilation is adjusted based on the level of CO_2 in the space [5]. Air quality control system is a possibility to use in ro-ro spaces as well [3] instead of the required capacity listed in SOLAS, but few ships have that implemented today. An air quality control system is combined with sensors and as a fire safety measure an idea is to link the system to gas detection and fire detection systems, in order to get early indications of a smouldering fires or gas leakages.

4.2 Permanent openings

Natural ventilation for open ro-ro spaces is provided by permanent openings in the side plating and weather decks shall be completely exposed to the weather, see the definitions below.

Open ro-ro spaces are those ro-ro spaces that are either open at both ends or have an opening at one end, and are provided with adequate natural ventilation effective over their entire length through ***permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10% of the total area of the space sides.*** (SOLAS II-2/3.35).

Weather deck is a deck which is completely exposed to the weather from above and from at ***least two sides***. (SOLAS II-2/3.50).

The current definitions include the word “side” which is open for interpretation. Also, the part of the definition describing permanent openings and the area of these, marked with bold in the text above, is open to interpretation. Together with the definition of weather deck which includes “at least two sides” it leaves it open to the reader (i.e. ship designer) what is a side and how to calculate the percentage of the total area of the space sides. Is a side only the long sides or are also short sides/ends, deck and deckheads included. It is found out through LASH FIRE partners that there is currently no internationally accepted best practise for what to include in the calculation of the opening percentage, neither a definition of a side. This might cause differences in how the calculations and classifications are made for ro-ro spaces. The interpretation of the Swedish Transport Agency is that the 10% is calculated with regards only to the long sides of the ro-ro space. A guidance of how to calculate the side openings in ro-ro spaces can start off like this:

- The calculation of 10% of the total area of the space sides should only consider the area of the long sides of the ro-ro space.

This means that it is only the long sides of a ro-ro space that should be considered when calculating the opening percentage. The deckhead, floor and short ends should not be considered in the calculations. It can also be questioned when a side is counted as a side, since many weather decks also have sides. See Figure 1 for example.

Figure 1: Ro-ro deck with closed sides, a weather deck.

An aspect of permanent openings is that a fire in the ro-ro space can spread out of the opening and affect other areas of the ship as well as equipment, people, and constructions. This problem is further described and studied in LASH FIRE Delivery D11.4 *Description of development and assessment of safe ro-ro space openings* [6] and the public report IR11.16 *Hull Exposure Levels Above Openings and Limits for Unprotected Areas* [7].

4.3 Field study

A field study was made on board Stena Jutlandica on 9 November 2021. A guided tour was held by a fire chief from the crew. Onboard ventilation design was studying as well as fire command on bridge and the instruction for ventilation in case of fire. Interviews were held with two of the onboard personnel, one chief engineer (fire chief on muster list) and one second mate/loading officer. The interviewees were used for understanding the crews' view on introducing a ventilation management strategy for fire scenarios in the ro-ro space.

The praxis today is to shut off the ventilation and close fire dampers when a fire is confirmed.

On Jutlandica, the exhaust air is driven by a fan. The supply air is only a duct with a damper, no fan. A signal is displayed when the damper is open/closed. Supply air is in the stern and the bow. Exhaust air is available on the port and starboard side, see Figure 2. Fan is started and stopped manually from the bridge. In case of fire, the fans are operated by the fire chief. In normal operation the ventilation system is operated from the bridge by the navigation officer/second mate. Dampers are started and stopped manually from the control room. There are two "modes" for the ventilation: one for loading in Gothenburg and one for loading in Frederikshavn. Jet fans are installed on deck 3. These are used during loading, to create mixing of air. See Figure 3.

Figure 2: Ventilation onboard

Figure 3: Jet fan on deck 3

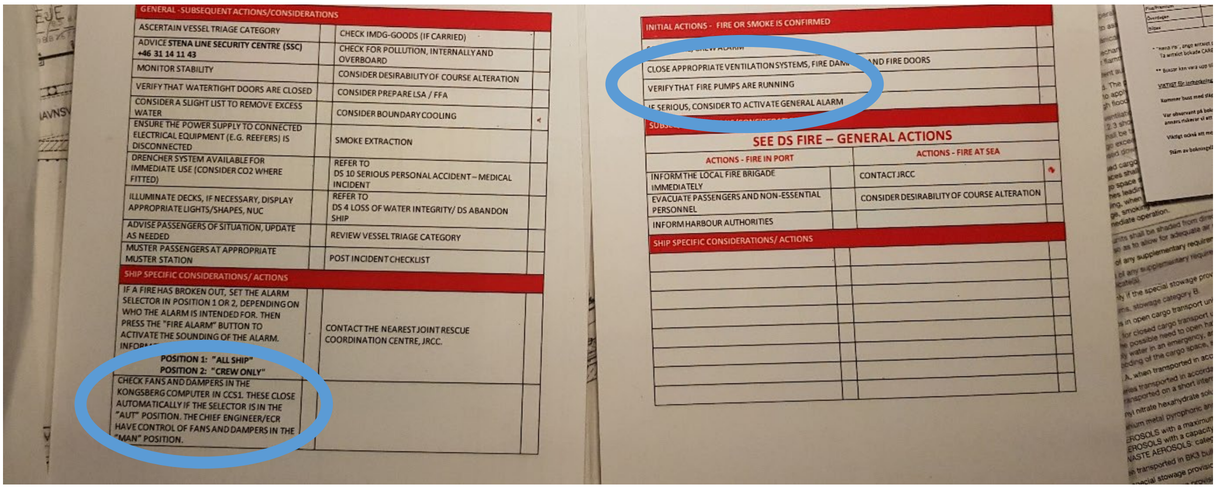
The interviews showed that there is an uncertainty surrounding how to best manage the mechanical ventilation during a fire. In previous experienced fire incidents, the fans were shut off during the fire and turned on to extract smoke after the fire had been extinguished. The interviewees had no knowledge of previous incidents where the mechanical ventilation had been used to facilitate manual operations during a fire.

The interviews showed that onboard personnel were optimistic towards introducing a ventilation management strategy in case of a fire. Clear instructions on when to activate and when to shut off the mechanical ventilation were brought up as important parts of such a ventilation management strategy.

Improved visibility was raised as a potential positive effect of using the mechanical ventilation during a fire, this had been experienced during exercises with smoke. It has worked well to evacuate smoke and the visibility is then increased. Increased fire intensity and influence of hot smoke on the ducts were raised as potential negative effects.

Regarding different types of fans it was mentioned that reversible fans are simpler than jet fans, but you cannot control them in different directions as with jet fans. Reversible fans are thus less flexible and there are fewer choices.

The crew described the function in case, nothing happens automatically with the ventilation system in the event of a fire alarm. The fire chief focuses on drencher. Dampers are closed manually. See instruction example in Figure 4.



GENERAL -SUBSEQUENT ACTIONS/CONSIDERATIONS

ASCERTAIN VESSEL TRIAGE CATEGORY	CHECK IMDG-GOODS (IF CARRIED)
ADVICE STENA LINE SECURITY CENTRE (SSC) +46 31 14 11 43	CHECK FOR POLLUTION, INTERNALLY AND OVERBOARD
MONITOR STABILITY	CONSIDER DESIRABILITY OF COURSE ALTERATION
VERIFY THAT WATERTIGHT DOORS ARE CLOSED	CONSIDER PREPARE LSA / FFA
CONSIDER A SLIGHT LIST TO REMOVE EXCESS WATER	CONSIDER BOUNDARY COOLING
ENSURE THE POWER SUPPLY TO CONNECTED ELECTRICAL EQUIPMENT (E.G. REEFERS) IS DISCONNECTED	SMOKE EXTRACTION
DRENCHER SYSTEM AVAILABLE FOR IMMEDIATE USE (CONSIDER CO2 WHERE FITTED)	REFER TO DS 10 SERIOUS PERSONAL ACCIDENT – MEDICAL INCIDENT
ILLUMINATE DECKS, IF NECESSARY, DISPLAY APPROPRIATE LIGHTS/SHAPES, NUC	REFER TO DS 4 LOSS OF WATER INTEGRITY/ DS ABANDON SHIP
ADVISE PASSENGERS OF SITUATION, UPDATE AS NEEDED	REVIEW VESSEL TRIAGE CATEGORY
MUSTER PASSENGERS AT APPROPRIATE MUSTER STATION	POST INCIDENT CHECKLIST

SHIP SPECIFIC CONSIDERATIONS/ ACTIONS

IF A FIRE HAS BROKEN OUT, SET THE ALARM SELECTOR IN POSITION 1 OR 2, DEPENDING ON WHO THE ALARM IS INTENDED FOR. THEN PRESS THE "FIRE ALARM" BUTTON TO ACTIVATE THE SOUNDING OF THE ALARM. INFOR[illegible] POSITION 1: "ALL SHIP" POSITION 2: "CREW ONLY"	CONTACT THE NEAREST JOINT RESCUE COORDINATION CENTRE, JRCC.
CHECK FANS AND DAMPERS IN THE KONGSBERG COMPUTER IN CCS1. THESE CLOSE AUTOMATICALLY IF THE SELECTOR IS IN THE "AUT" POSITION. THE CHIEF ENGINEER/ECR HAVE CONTROL OF FANS AND DAMPERS IN THE "MAN" POSITION.	

INITIAL ACTIONS - FIRE OR SMOKE IS CONFIRMED

[illegible] CREW ALARM
CLOSE APPROPRIATE VENTILATION SYSTEMS, FIRE DAM[illegible] AND FIRE DOORS
VERIFY THAT FIRE PUMPS ARE RUNNING
IF SERIOUS, CONSIDER TO ACTIVATE GENERAL ALARM

SUBS[illegible]

SEE DS FIRE – GENERAL ACTIONS

ACTIONS - FIRE IN PORT	ACTIONS - FIRE AT SEA
INFORM THE LOCAL FIRE BRIGADE IMMEDIATELY	CONTACT JRCC
EVACUATE PASSENGERS AND NON-ESSENTIAL PERSONNEL	CONSIDER DESIRABILITY OF COURSE ALTERATION
INFORM HARBOUR AUTHORITIES	

SHIP SPECIFIC CONSIDERATIONS/ ACTIONS

Figure 4: Instruction regarding fans and ventilation in event of fire

4.3.1 Implementation of field study

The information received from the field study (including interviews) were used as inputs for the development of the safety measure:

- Usage of reversible fans for closed ro-ro spaces (to facilitate manual interventions).

The interviews and discussions supported a notion to only consider the usage of fans in the early stages of a fire in a closed ro-ro space. This is a scenario where the fire spread has not propagated more than to a level where it is still possible to do some manual intervention, the drencher can be assumed to be both on and off.

A 5 MW fire was decided to be used as a definition for the early phase of the fire in the following simulations and tests, this because it is commonly used as design value for heat release rate for a single burning car, see [8] and [9]. It was made clear, however, that it is hard for the crew know when the limit of 5 MW is reach, both because it can be hard to visible see a fire and what is burning, and also the fire intensity.

5 Regulations review concerning ro-ro space ventilation

Main author of the chapter: Blandine Vicard and Eric de Carvalho, BV

This chapter aims at giving an overview of the requirements applicable in ro-ro spaces regarding ro-ro space ventilation and smoke extraction.

5.1 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 ships. A brief summary of the main regulation changes related to ro-ro space ventilation and smoke extraction is provided in Table 1. The review is mainly based on the documents listed in Table 2.

Table 1: Summary of regulation changes

Regulation change	Application date	Adoption date	Summary
SOLAS 74	1980	1974	Introduces the general principle of ventilation for ro-ro and vehicle spaces, including minimum air changes per hour and segregation with respect to other spaces
MSC.365(93)	01/01/2016	22/05/2014	Update of SOLAS requirements for the insulation of ventilation systems (SOLAS II-2/9.7). No major impact for ventilation of ro-ro and vehicle spaces
MSC.392(95)	01/01/2017	11/06/2015	Introduces the option for a reduced number of air changes in ro-ro and vehicle spaces, as detailed in 5.2.2.2

Table 2: List of documents used for the review of regulations for [Objet]

IMO Documents	SOLAS Convention, as amended
	MSC.1/Circ.1120
	MSC.1/Circ.1434
	MSC.1/Circ.1515, Revised design guidelines and operational recommendations for ventilation systems in ro-ro cargo spaces
	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
International Association of Class Societies (IACS) & Class Rules	IACS Blue book dated January 2020
	Bureau Veritas (BV) Rules for Steel Ships (NR467), as amended in July 2020
	DNVGL Rules for classification, ships, as amended in July 2020
Flag Administration Rules	MMF (French Flag Administration) Division 221 “Passenger ships engaged in international voyages and cargo ships of more than 500 gross tonnage”, 11/01/2020 edition
	US Coast Guard (USCG) Code of Federal Regulations (CFR) 46, 2019 online edition
	MCA (UK Flag Administration) Guidance on SOLAS Chapter II-2

5.1.1 Definitions

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

5.1.1.1 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.”*[1]
- *“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.

5.1.1.2 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.

5.2 Requirements

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

5.2.1 Ro-ro and vehicle spaces permanent openings

As a general principle, SOLAS III/13.1.5 requires that “Each survival craft shall be stowed as far as practicable, in a secure and sheltered position and protected from damage by fire and explosion.” In addition and more widely, SOLAS II-2/20 requires that permanent openings be so located that “a fire in the cargo space does not endanger stowage areas and embarkation stations for survival craft and

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[1] 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”.

accommodation spaces, service spaces and control stations in superstructures and deckhouses above the cargo spaces."

[SOLAS II-2/20.3.1.5]

As a side note, it can be outlined that, although this requirement is found under the headline "3 Precaution against ignition of flammable vapours in closed vehicle spaces, closed ro-ro spaces and special category spaces", it is usually also taken into account for open ro-ro and vehicle spaces as well.

It nevertheless remains very qualitative and therefore its application relies on the appreciation of the Flag Administration. Chinese Flag Administration, in their domestic regulations, consider that 3 m distance between ro-ro space openings and survival craft stowage areas or embarkation stations is sufficient [10].

Furthermore, European Maritime Safety Agency (EMSA), following the FIRESAFE II study [11], has been proposing minimum distances between permanent openings in the sides and ends of ro-ro spaces and survival craft, which resulted in IMO *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, MSC.1/Circ.1615, recommending at least 6 m measured horizontally between a cargo space side opening and survival craft, marine evacuation systems, embarkation stations and muster stations.

[MSC.1/Circ.1615 §5]

5.2.1.1 Ban of openings

One step further to the measures mentioned above consists in banning openings in ro-ro and vehicle spaces, as recommended by IMO *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*, MSC.1/Circ.1615 [12].

[MSC.1/Circ.1615 §4.2]

5.2.2 Mechanical ventilation purpose and required capacity

5.2.2.1 General case

Ro-ro spaces are reckoned to be hazardous spaces where an explosive atmosphere may occur – basically due to vehicle fuel vapours. Significant ventilation is therefore required in these spaces as a mitigation measure to avoid ignition of an explosive atmosphere. It is to be noted that other measures are also taken to avoid ignition of explosive gases, including restrictions on possible sources of ignition.

SOLAS II-2/20.3.1.1 requires the following capacity for the ventilation systems of closed ro-ro spaces:

Table 3: Required ventilation rate in closed ro-ro spaces.

Type of ship	**Ro-ro space**	**Required ventilation rate [air changes per hour]**
Passenger ship carrying more than 36 passengers	Any	10
Passenger ship carrying not more than 36 passengers	Special category spaces	10
	Other closed ro-ro and special category spaces	6
Cargo ships	Any	6

For practical purposes, open ro-ro spaces and weather decks are naturally ventilated, and no minimum ventilation capacity is therefore specified.

SOLAS II-2/20.3.1.1

Some Flag Administrations have slightly different requirements. For example, the USCG CFR [13] specify a ventilation rate of 1ft^3/min for each square foot of deck area of vehicle space, i.e. about 6 air changes per hour considering a typical deck height of 10ft in the vehicle space. They also specify that the ventilation should be of the overpressure type.

USCG 46 CFR 92.15-10 and 46 CFR 72.15-15

The ventilation system shall be such as to prevent air stratification and the formation of air pockets.

SOLAS II-2/3.1.2.3

In addition, a number of Flag Administrations specify a higher number of air changes during loading and unloading: French Flag Administration requires 15 air changes per hour. The USCG [12] require carbon monoxide content to be monitored when vehicles are to be used in enclosed spaces.

MMF division 221 – II-2/20.3.1.1, USCG 46 CFR 97.80-1 & 46 CFR 78.83-1

5.2.2.2 Reduced ventilation rate

In case an air quality control system is provided, complying with the requirements of MSC.1./Circ.1515 [3], as detailed in section 5.2.2.3 below, the ventilation rate may be decreased. It is to be noted that air quality control is based on gasoline vapour and toxic exhaust gas measurements. Therefore, it is not applicable in 3 cases:

- Carriage of dangerous goods (covered by SOLAS II-2/19): Because SOLAS II-2/19] does not include provisions for hazardous gases generated by dangerous goods;
- Vehicle carrier carrying hydrogen-fuelled vehicles (covered by SOLAS II-2/20-1): Because hydrogen explosive atmospheres are not considered in MSC.1./Circ.1515; and
- When an increased ventilation rate (10 air changes per hour) is used as a mitigation measure to reduce the level of protection of the electrical equipment, as allowed by SOLAS II-2/20.3.2.2.

SOLAS II-2/20.3.1.2

5.2.2.3 Air quality control system

When provided with a view to operating with reduced ventilation capacity, the air quality control system is to automatically regulate the ventilation rate based on measurements of CO, NO_2 and LEL values, so that the threshold values are never exceeded over a 5-minute period. The threshold values are long-term exposure values and are defined based on ISO 9785:2002 Ships and marine technology — Ventilation of cargo spaces where vehicles with internal combustion engines are driven — Calculation of theoretical total airflow required; they are reproduced in Table 4. In addition, a visual and audible alarm is to be given at a continuously manned location in case the threshold values for those pollutants are exceeded.

MSC.1/Circ.1515 Appendix 1 §1, 2.1, 2.3, 3.1, 3.2, 4, 6

Table 4: Pollutant threshold values

Pollutant	Threshold value
CO	40mg/m3
NO_2	4mg/m3
Flammable gas	10%LEL

MSC.1/Circ.1515 Appendix 1 §4.2

Detailed provisions are given with a view to:

- Ensuring proper design and location of the sensors for an efficient monitoring of the pollutant level. In addition to general design and considerations, a performance test on board is required – it may be replaced by a model test.

MSC.1/Circ.1515 Appendix 1 §2.1, 2.6, 2.9, 3.1, 3.3, 4.3, 5

- Ensuring proper operation, calibration and maintenance of the sensors and pollutant monitoring system.

MSC.1/Circ.1515 Appendix 1 §2.2, 2.7, 2.9

- Minimizing the risk of loss of power and informing the crew in case of failure, especially power failure of the air quality control system. In this situation, the ventilation system is to return automatically to its nominal capacity, as required without air quality control system.

MSC.1/Circ.1515 Appendix 1 §2.4, 2.5, 2.8, 2.10, 2.11

5.2.2.4 Ventilation equipment

In general, ro-ro and vehicle spaces are reckoned as hazardous areas. As a consequence:

- Exhaust fans are to be non-sparking; and
- If located in the exhaust duct, fan motors are to be of an adequate certified safe type. Otherwise, they may be located outside the ventilation duct.

SOLAS II-2/20.3.3 as interpreted by IACS UI SC 43 and MSC.1/Circ.1120

As a complement, UK MCA requires that most of the fans serving ro-ro or vehicle spaces be located in a dedicated space, separated from the ro-ro or vehicle spaces.

UK MCA Guidance on Ch II-2 – G1.1

5.2.2.5 Ventilation controls

For each ro-ro or vehicle space, it is to be possible to:

- Control (i.e. start and stop) the ventilation system; and
- Close all ventilation openings.

From outside these spaces, taking into account weather and sea conditions. Remote control arrangements with position indicators may also be accepted.

SOLAS II-2/20.3.1.2 & 20.3.1.4, as interpreted by IACS UI SC 243 and IMO MSC.1/Circ.1434

In addition, the ventilating capacity is to be monitored from the navigation bridge. An alarm initiated by fall-out of the starter relay of the fan motor is deemed acceptable in this respect.

SOLAS II-2/20.3.1.3, as interpreted by IACS UI SC75 and IMO MSC.1/Circ.1120

5.2.2.6 Testing of the ventilation system

MSC.1/Circ.1515 includes maintenance recommendations for the ventilation system and especially testing recommendations:

- Testing of the ventilation system at ship delivery by a Third Party;
- Testing every year by the ship’s crew or operator; and
- Testing by a Third Party every 5 years.

IMO MSC.1/Circ.1515 Annex Part 2 §2 and 3

It is to be noted that Classification Societies' survey requirements and do not explicitly mention testing following the test procedure detailed in MSC.1/Circ.1515 Appendices 2 and 3, rather verification that the ventilation system is in working order at each annual survey.

BV NR467 Rules for the Classification of Steel Ships, Pt A, Ch 4, Sec 6 [2.3]

DNVGL Rules For Classification: Ships, Pt 7, Ch 1, Sec 2 [3.1.17]

5.2.3 Operational recommendations

5.2.3.1 During normal operation

MSC.1/Circ.1515 [6] includes operational recommendations for the ventilation system and, more generally, avoiding exposing people to polluted air or generating explosive mixtures. These include:

- Ensuring that the air flow will not be impeded (free ventilation inlets and outlets, avoid overcrowded areas and other obstructions);
- Adapt the ventilation air flow to the operational situation and environmental conditions;
- Avoid sending people to carry out unnecessary work during periods when a significant quantity of pollutant can be generated, e.g. loading/unloading; and
- Manage loading/unloading procedures so as to reduce the period when vehicle engines need to be running, with considerations dedicated to each ship type.

IMO MSC.1/Circ.1515 Annex Part 2 §4

5.2.3.2 In case of fire

In case of fire situation, there is no specific action requirements from the IMO regulations to activate or shutdown the mechanical ventilation of ro-ro spaces nor to open or close openings. Those actions should be understood as operational and up to on-board procedures or to master's and/or crew's appraisal depending on the fire situation. Nevertheless, the IMO regulations provide the possibility to perform such actions (as described in the above sections).

5.2.4 Fire containment

Ventilating systems are specifically scrutinized when considering fire insulation, as they may be a weak point in this respect. Ro-ro and vehicle spaces are reckoned to be spaces with high fire risk, and, in this respect, the following is required for their ventilation systems in order to avoid propagating a fire to other spaces:

- The ventilation systems for ro-ro and vehicle spaces are to be separate from each other and from ventilation systems serving other types of spaces.
- Ducts serving other spaces and crossing ro-ro or vehicle spaces and ducts serving ro-ro or vehicle spaces and crossing other spaces are to be of substantial thickness and either insulated to A-60 standard over their whole length or provided with an automatic fire damper close to the boundary penetrated and insulated to A-60 standard over 5m. For ducts serving ro-ro or vehicle spaces and crossing category A machinery spaces, the first option is mandatory.

SOLAS II-2/9.7.2 & II-2/20.3.1.4.2, as interpreted by IMO MSC.1/Circ.1120

The required automatic fire dampers are to:

- Close automatically, in response to exposure to fire products (e.g. heat);

SOLAS II-2/3.54

- Have a failsafe mechanism that will close the damper in a fire even upon loss of electrical power or hydraulic or pneumatic pressure loss; and

SOLAS II-2/9.7.3.3

- Be manually operable from both sides of the boundary penetrated, i.e. being capable of being closed and re-opened manually.

SOLAS II-2/9.7.3.3

No remote control is required for those dampers.

6 Ship integration requirement definitions

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This chapter gathers the requirements for ro-ro space ventilation in terms of ship integration aspects.

6.1 Requirements and restrictions due to the rules and regulations

This topic is covered in-depth in previous chapter, 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.

6.1.1 The definitions and classifications of ro-ro cargo spaces

There are two main classification of ro-ro cargo spaces: one regarding the type of ro-ro cargo and second depending on how open the ro-ro space is to the outside air. The classification according to the type of ro-ro cargo is not very well and clearly distinguished, in our opinion. In particular, there is ro-ro space, which should be the overall name for all such spaces, as per SOLAS definition:

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 in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks in or on similar stowage units or other receptacles) can be loaded and unloaded in any horizontal direction.

Ro-ro space is further subdivided on special category spaces and vehicle spaces. The definition of special category space is:

Enclosed spaces above or below the bulkhead deck intended for the carriage of motor vehicles with fuel in their tanks for their own propulsion, into and from which such vehicles can be driven and to which passengers have access.

The definition of vehicle space is as follows:

Cargo space intended for carriage of motor vehicles with fuel in their tanks for their own propulsion.

Much of the IMO regulations also includes a **ro-ro cargo spaces** term, which is not clearly defined, whether it is meant to be a third subdivision of **ro-ro spaces**, or as a global definition of all such spaces. For instance, in the classification of space use in accordance with fire risk, it is stated that the ro-ro spaces are the areas of major fire hazard while IMO MCS.1/Circ.1515 has a title *Revised Design Guidelines and operational Recommendations for Ventilation Systems in Ro-Ro Cargo Spaces*. This should be better explained in the future SOLAS editions. Another explanation could be that the terminology in SOLAS Amendment 1996 was ro-ro cargo spaces defined and that the IMO regulations have not been updated while the terminology has been so.

The second classification of ro-ro spaces is depending on how open such space to the outside air is. There are three categories: weather deck, open ro-ro spaces and closed ro-ro spaces. A clear definition of “space sides” is lacking in SOLAS and shall include what is a side and how high structure should be to be a side. A clear guidance of how to calculate the openness of an open ro-ro space can also be included, to avoid different Class interpretations. What is also not clear is a background of open ro-ro space definition regarding 10% of the total area of the space sides, whether it is derived from mathematical formula or from empirical evidence. It is also not clear whether the openness of the space sides in closed ro-ro spaces variating up to 9% should be completely banned, as it is almost as vulnerable as an open ro-ro space in case of fire incident (as concluded in [1]).

“Permanent openings” could, in this context, be understood to be also ventilation outlets and relate to any type of ro-ro space not only open decks. This is however in need of being defined in the rules for a common understanding of what is included in “permanent openings”.

6.1.2 Ventilation system in ro-ro spaces

Functional requirement of ro-ro cargo space ventilation system is that:

Vehicle, special category and ro-ro spaces shall be adequately ventilated.

as per SOLAS II-2/20.1.3.

Such adequate ventilation is further described in SOLAS II-2/20.3.1.1 Capacity of ventilation system.

For all cargo ship and all closed ro-ro and vehicle spaces other than special category spaces for ships carrying not more than 36 passengers, the capacity of ventilation system shall be at least 6 air changes per hour (ACPH). For all special category spaces and all closed ro-ro and vehicle spaces for ships carrying more than 36 passengers, it is required at least 10 air changes per hour. SOLAS 20.3.2.2 allows 6 ACPH for above mentioned ships and ro-ro cargo spaces if the electrical equipment is of certified safe type in the entire space, or it should be again 10 ACPH if the electrical equipment is of certified safe type up to the height of 450 mm above the deck.

The required ACPH (both from SOLAS or from individual Class Societies) deserves to be furtherly elaborated, whether these numbers have mathematical or empirical background. The power ventilation system shall be operated to give at least the number of air changes required above at all times when vehicles are in such spaces, except where an air quality control system is provided. Further, as per SOLAS II-2/20.3.1.2.4 states that

For all ships, where an air quality control system is provided based on the guidelines by the Organization (refer to the Revised design guidelines and operational recommendations for ventilation systems in ro-ro cargo spaces – MSC.1/Circ.1515), the ventilation system may be operated at a decreased number of air changes and/or a decreased amount of ventilation.
This relaxation does not apply to spaces to which at least ten air changes per hour is required by paragraph 3.2.2 of this regulation and spaces subject to regulations 19.3.4.1 and 20-1.

SOLAS II-2/19.3.4.1 and 20-1 deals with carriage of dangerous goods and hydrogen-powered vehicles and due to the variety of all possible hazardous gases and explosive nature of hydrogen it is understandable that the strong ventilation is the only alternative at the moment. A good way forward would be to introduce the methane and hydrogen gases in air quality control system also. However, in case of passenger ship owners and operators that are ready to go beyond the rules and regulations in order to increase fire safety on their ships investing in such technologies monitoring the air quality in the ro-ro spaces, there is no bonus comparing to the others simply following the minimal rules. The background of such decision deserves to be further discussed. As of carriage of dangerous cargo, it is required that *Adequate power ventilation shall be provided in enclosed spaces. The arrangement shall be such as to provide for at least six air changes per hour in the cargo space based on an empty space and for removal of vapours from the upper or lower parts of the space, as appropriate*.

As per SOLAS II-2/3.1.1 *The administration may require an increased number of air changes when vehicles are being loaded and unloaded.* Certain Class Societies further describe this requirement by exact number of 20 ACPH at the quayside during vehicle loading and unloading operations. Again, it is not clear what is the background of this requirement.

Concerning natural ventilation it is assumed that the same number of air changes is required in weather decks and open ro-ro cargo spaces. There is thus no requirement for any additional mechanical ventilation for these spaces. Permanent openings have general requirement about their longitudinal location, as per SOLAS II-2/20.3.1.5:

Permanent openings in the side plating, the ends of 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.

Other than that, nothing else can be found in SOLAS regarding permanent openings for natural ventilation, concerning geometrical shape, size, position etc. This regulation is currently proposed to be changed through the ongoing IMO discussions and 2024 revision of SOLAS.

SOLAS II-2/20-1 is added in SOLAS dealing with the requirements for vehicle carrier carrying motor vehicles with compressed hydrogen or natural gas in their tanks for their own propulsion as cargo. Concerning the ventilation of such spaces, the same requirements shall comply as for common ro-ro cargo spaces, except that the electrical equipment, wiring and fans shall be of certified safe type for use in explosive methane and air mixtures, or explosive hydrogen and air mixtures, respectively. The requirement for electrical equipment was introduced for vehicle carriers constructed from 2016-01-01.

MSC.1/Circ.1515 [3] REVISED DESIGN GUIDELINES AND OPERATIONAL RECOMMENDATIONS FOR VENTILATION SYSTEMS IN RO-RO CARGO SPACES (which supersedes old MSC/Circ.729) gives the very general principles and some operational and testing recommendations. Ventilation system for ro-ro cargo spaces on board ship generally operate according to the principle of dilution ventilation, whereby the supply air flow to the area is sufficient for the exhaust gasses to mix thoroughly with the air and be removed. This document also describes the function of a ventilation system in a ro-ro cargo space, which is to dilute and remove the vehicle exhaust gases and other hazardous gases. The basic particulars necessary for calculating the supply air required are contained in ISO 9785:2002 SHIPS AND MARINE TECHNOLOGY – VENTILATION OF CARGO SPACE WHERE VEHICLES WITH INTERNAL COMBUSTION ENGINES ARE DRIVEN – CALCULATION OF THEORETICAL TOTAL AIRFLOW REQUIRED. *This International Standard specifies methods of calculating the theoretical quantity of outdoor air required in cargo spaces of ships where vehicles with internal combustion engines are driven, in order to dilute the polluted air to within the permitted occupational exposure limits.* It can be achieved by limiting the exhaust gases (controlling the traffic) as far as possible and/or providing a suitable air flow in the space.

The volume of total cargo spaces, while doing the airflow calculations, shall be the gross volume with no deduction for the cargoes or for frames, webs, pillars, ducts etc. In the case of lining or insulation of cargo spaces, the volume shall be calculated from the inside of the lining or insulation.

The outdoor-supply airflow to the cargo spaces shall be calculated using whichever of the following criteria gives the highest value:

- *minimum number of air changes according to applicable statutory requirements;*
- *required outdoor-supply airflow to maintain the occupational-exposure limit-value.*

The method also considers the degree of estimated dilution of the air pollution in the cargo spaces, as well as average values of pollutants in exhaust gases from different vehicles on board ships. These values seem to be outdated and should be at least checked and revised, if needed, in our opinion. The alternatively powered vehicles (APV), such as LNG, CNG and battery-powered vehicles should be also considered and included.

SOLAS II-2/20.3.1.2.1 states that the power ventilation system shall be separate from other ventilation systems, in passenger ships. For cargo ships, the corresponding regulation is written in SOLAS II-2/20.3.1.2.2: “The system shall be entirely separate from other ventilation systems. Ventilation ducts serving ro-ro or vehicle spaces shall be capable of being effectively sealed for each cargo space.”

Dampers on vehicle carriers are usually located on weather deck level which means that the ducts are part of the vehicle space. It is not practical to have the damper located at the boundary of space with difficult access.

SOLAS 2-II/9.7.2.1: “The ventilation systems for machinery spaces of category A, vehicle spaces, ro-ro spaces, galleys, special category spaces and cargo spaces shall, in general, be separated from each other and from the ventilation systems serving other spaces. It also states that 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.

As per SOLAS II-2/9.7.2.2, ventilation ducts serving a ro-ro space and crossing accommodation spaces, service spaces or control stations are required to:

- Be made of steel with suitable thickness and to be suitably supported and stiffened.
- Be either provided with an automatic fire damper close to the boundaries penetrated + A-60 insulation on 5 m beyond the damper **or** A-60 insulated throughout the spaces they pass through.

Requirements extended in above direction will influence location of ventilation outlets, damping functions and how ventilation system may be operated.

If, for any reason, permanent side openings in open ro-ro space are significantly limited in localization and size, this may influence the natural ventilation function at such decks. One condition for an open deck is evenly distributed openings.

6.2 Operational aspects

6.2.1 Consideration on closed ro-ro decks

Ventilation system is a significant system onboard in terms of investment, power need, space claim and maintenance. Therefore, it should be carefully designed and optimized according to the design of the individual ship and the operational vehicle handling and exhaust emissions accumulation connected with it. MSC.1/Circ.1515 considers four main measures:

- a reduction in exhaust gas emissions,
- provision of an adequate ventilation system,
- limitation of exposure to the gases,
- prevention of accumulation of hazardous and flammable gases.

The operational recommendations are primarily directed at those involved with cargo handling in ro-ro cargo spaces. Their purpose is to suggest ways in which exposure to exhaust gas emissions can be restricted and to avoid accumulation of potentially hazardous and flammable gases. These recommendations can be divided in four main parts: testing of the ventilation system, training and information, inspection, maintenance and repairs and recommendations for cargo operations.

Some tests are Class requirement and should be performed before the actual delivery of the ship (air change rate), but it is very important to also test the actual air distribution and the air quality in the ro-ro cargo spaces. The testing should be repeated in regular intervals, and in situations which indicate the necessity, whether based on worker complaints or substantial changes in vessel operation. All test results verifying the adequacy of the ventilation system should be documented and kept on board. The ventilation system operation procedures should be established based on mentioned test results and according to the cargo operations.

Furthermore, the personnel should be properly trained and familiarized with established procedures. However, there are no specified procedures, only IMO recommendation to establish it. Usually, first training and familiarization is performed during the actual building and testing process of the ventilation system. A process should be also established to record and investigate complaints for poor air quality by crew and stevedores. Drivers should be given appropriate instructions for embarkation or disembarkation. Training and information should be reviewed following a significant change in the operation of the vessel.

Inspection, maintenance, and necessary repairs should be carried out professionally and in regular intervals (annually). Necessary skills, equipment and spares should be always available. Third party testing should be undertaken before entry into service of a new ship and at periodical intervals thereafter.

Loading and unloading operations are by far the most critical operations regarding health hazard. It is therefore extremely important that the ventilation system is operated in the most effective manner under the prevailing operational and weather conditions. The personnel responsible for loading and unloading of vehicles should consult with the officer responsible for vehicle deck ventilation to familiarize himself with the ventilation system on board and decide whether the ventilation is adequate in the light of traffic density, vehicle types and other considerations. It is also important to ensure free passage of supply air and that ventilation openings are not unnecessarily obstructed. Vehicles should spend as little time as possible on board with their engines running. The speed at which the vehicles are driven on board should also be appropriate to the prevailing conditions. Exhaust emissions are greatly influenced by driving techniques and the temperature at which an engine is running. The essential points are as follows, according to MSC.1/Circ.1515 Part 2:

- condition of the engines
- driving techniques
- organization of the work (as few engines as possible running at the same time)
- the drivers should not start their engines sooner than necessary (in case of unloading)
- ensuring the steady flow of the traffic (eliminating heavy acceleration and high speeds) – little effect during disembarkation due to cold engines.

The drivers should be given printed instructions for embarkation/disembarkation and driving techniques, which is especially important in case of car ferries.

Ventilation systems in the cargo ships may be operated at decreased capacity (SOLAS II-2/20.3.1.2.4) when controlled by a detection system that monitors the flammable and harmful gases in the space. Air quality management is based on the measuring and controlling of CO, NO2 and LEL values.

In cargo ships, ventilation fans shall normally be run continuously whenever vehicles are on board. Where this is impracticable, they are to be operated for a limited period daily as weather permits and in any case for a reasonable period prior to discharge, after which period the ro-ro or vehicle space shall be proved gas-free. One or more portable combustible gas detecting instruments are to be carried on board for this purpose.

According to ship operators taking part in the project, the most common way to operate the ventilation system in case of fire is to turn it off and to close fire dampers, however, the responsibility remains on captain, whether following the standard procedure or not, after the evaluation of the situation. Impact of drencher on air circulation must be understood, which could have a significant impact on airflow and temperature of gases during a fire scenario.

6.2.2 Considerations on open ro-ro decks

Historically, deck volumes located transversely inside side openings and inside aft and forward openings could be excluded from the net tonnage. This is however not anymore allowed, and all spaces intended for carriage of cargo should be included in net tonnage. Therefore, closure/banning of side openings will not affect net tonnage or port or fairway fees that are based on net tonnage.

According to the International Maritime Dangerous Goods (IMDG) Code, the Administration may allow carriage of certain dangerous cargo on open ro-ro cargo space, for example DG classes where main risk factor is emission of gases. Also, livestock may be carried and reefer units running on diesel.

If open ro-ro cargo space is not allowed, electric connection sockets with cables for reefers shall be installed, leading to additional components, installation, and operation/maintenance cost, as well as added fire risks. Open ro-ro cargo space is provided with natural ventilation, thereby mechanical ventilation system is not required, which reduces cost in terms of investment, power requirements, space claim and maintenance. If the openings would be closed, electrical power requirements would increase due to the ventilation system and reefer connection sockets requirements, with negative environmental impact due to increased fuel consumption and increased operational and investment cost. Consequences on the cargo stowage and loading/unloading operations from closure of end openings must be investigated thoroughly, as may lead to loss of cargo capacity, available space for dangerous goods and increased of time in port.

The value of a “small” weather deck aft of a closed ro-ro cargo space will increase if the open ro-ro cargo space is prohibited, since dangerous goods capacity is limited. Efficiency of such weather decks must be secured to preserve efficiency of vessels.

According to RO5 [1] maximum 4% of all side/aft/forward boundaries may be allowed to keep oxygen supply under control and thereby prevent excessive fire growth.

6.2.2.1 Other openings

In the open ro-ro cargo space, there can be other openings arranged, not intended for natural ventilation, intended for ship systems/equipment as follows:

- Mooring
- Bunker boat mooring
- Accommodation ladder
- Pilot access
- Access to Man-Over-Board boat
- Access to LSA equipment
- Bunkering operation

6.2.3 Considerations on weather decks

Different weather decks designs give very different ventilation conditions. Weather decks are not further discussed or analysed in this report.

6.3 Design and production aspects

6.3.1 Mechanical ventilation

It is very complex to design the ventilation for a ro-ro space. Every ship is unique and therefore no templates or standard calculations can be used. In MSC.1/Circ.1515 it is clear *that it is not possible to draw up or recommend any universal solutions for the distribution of air flow in different type of ship.* The following general applications are written in the MSC.1/Circ.1515 Part 1:

- *The air flow should reach all parts of the ro-ro cargo space. However, ventilation should be concentrated in those areas in which the emissions of exhaust gases are particularly high and which are occupied by the crew or other workers.*
- *Consideration should be given to the likelihood of unventilated zones being screened behind an object, and also to the fact that exhaust gases readily accumulate in low-lying spaces under the vehicles and in decks beneath the one being unloaded. Furthermore, depending on air flow patterns, it may be possible for contaminants to move into decks above the one actually being offloaded.*
- *The air flow on vehicle deck should be suited to the height of the deck.*
- *The air flow will follow the path of least resistance, and most of the air will thus flow in open spaces, such as above the vehicles, etc.*
- *Polluted air from ro-ro cargo spaces should be prevented from being dispersed into adjacent spaces, for instance accommodation and engine-rooms.*
- *Whenever possible, places which are sheltered from the airflow should be indicated on the plan. The actual locations of such spaces on the deck should be painted in a conspicuous manner to indicate that personnel should not stand on that part of the deck, and signs should be hung on the bulkhead to provide a backup warning.*

Ventilation systems for ro-ro cargo spaces on board ships generally operate according to the principle of dilution ventilation.

There are two main types of dilution ventilation: exhaust air ventilation and supply air ventilation. In exhaust air ventilation, the air from ro-ro cargo space is removed with fans and air change is ensured by outdoor air entering through open ramps, doors, and other openings. Exhaust air ventilation is employed when sub-atmospheric pressure is required in the ro-ro cargo space, which prevents the pollution from spreading to adjacent areas. In supply air ventilation, fans deliver outdoor air into ro-ro cargo space and the air is then exhausted through ramps and other openings. Supply air ventilation usually creates slight pressurization of the ro-ro cargo space. If used exclusively, pollutants may mix with the supply air, be pushed up the internal ramps and contaminate other decks. Besides, contaminants may remain on the deck in question, if not sufficiently mixed with supply air – hazardous conditions may occur on lower decks.

Ventilation system on board ship often combine these two principles, especially when ships has both stern and stem ramps. The fans can also be reversible, but the operator must be aware to the fact that reversible fans cannot obtain full capacity in both modes (supply and exhaust).

Exhaust gas dispersion will never be uniform. It is dependent upon the capacity, design, and mode of operation of the ventilation system, also the volume and configuration of the cargo space as well as natural ventilation patterns and location of vehicles in ro-ro cargo spaces. Even though the overall rate of air change on vehicle decks may be high, there will also be areas with low rates of air change and should be located, indicated, and painted. Air requirements should be calculated according to ISO 9785:2002 which may be used as reference in the planning of new installations.

In addition to ensure given rate of air changes for certain ro-ro cargo space, it is equally important to ensure proper air circulation in the same space. *Duct runs and the location of supply air and exhaust* *air openings should be made to suit the design of the individual ship, the estimated vehicle handling and exhaust emissions in such areas. The air flow can be determined by means of direct measurement or by calculation-based methodology (CFD and/or use of established empiric formulae).*

ISO 9785:2002 gives following general considerations for ventilation systems and ducting:

- *supply air and exhaust air openings should be located so that the ventilation will be concentrated to those areas in which the emissions of exhaust gases are particularly high and in which crew work*
- *supply air and exhaust air openings should be located, wherever possible, where they will not be obstructed by the cargo or screened by ship's structure*
- *supply air and exhaust air openings should be designed so that the maximum air velocity in the openings does not exceed 10 m/s (recommendation only)*
- *Considerations should be given to the likelihood of there being unventilated zones screened behind objects, and also to the fact that exhaust gases readily accumulate in low-lying spaces and under the vehicles*
- *the airflow will follow the path of least resistance and most of the air will thus flow in open spaces, such as above for cargo, vehicles etc.*
- *measures should be taken to prevent polluted air from cargo spaces from dispersing into adjoining spaces where people can be exposed, such as accommodation, engine room etc.*

The ventilation system shall be such as to prevent air stratification and the formation of air pockets.

Certain Class Societies (e.g., DNVGL) require independent power ventilation system to be provided for the removal of gases and vapours from the upper and lower part of the ro-ro cargo spaces on cargo ships. This requirement is considered to be met if the ducting is arranged such that approximately 1/3 of the air volume is removed from the upper part and 2/3 from the lower part.

ISO 9785:2002 gives the guidance for estimating the flow of outdoor air required to dilute and remove the exhaust gases and for assessment of the number of vehicles which may be in operation at the same time in a ro-ro cargo space. The guidance specifies the supply air requirement per vehicle, to ensure that the level of pollution is kept below the exposure limit.

In general, the design procedure for ro-ro cargo space ventilation system should include the following measures:

- Satisfy the rules requirements, among others related to required exchange of air (in port and seagoing)
- Optimize the arrangement of ventilation trunks or ducts, i.e. number of trunks, ventilator required properties, etc.
- Avoid interference with other equipment
- Must be easy to operate, preferably from several access points
- Easy maintenance
- Minimize the interference with the cargo area and passenger area

Testing the ventilation system prior to the delivery of the ship must be performed in order to confirm that the design air change and air flow is obtained. The test results apply to empty vehicle spaces and the weather prevailing at the time of testing. But, to utilize the ventilation system in the ro-ro cargo spaces on a ship in most effective way, knowledge should be acquired of its capacity from experience and through simple tests. The factors that need to be determined are the quantities of air supplied to and exhausted from the ro-ro cargo spaces and the circulation of air within the vehicle deck. It is very important that the conditions prevailing at the time of the test, which influence the results, are carefully documented since air flow patterns will vary according to loading conditions.

The rate of air change is a Class requirement test, performed for each vessel, and usually determined by measuring the flow of air on each ventilation opening using a direct reading of anemometer. Sometimes, on Owner's request, the smoke test is performed. The smoke test is a visual test using visible smoke, which provide sufficient indication of a satisfactory picture to be obtained of the air circulation, the existence of any possible stagnant or screened zones and the rate at which pollutants are removed by designed ventilation system.

6.3.2 Natural ventilation

From the open ro-ro cargo space design and production point of view, the following shall be considered:

- Satisfy the rules requirements so the cargo space can be considered "open ro-ro space",
- maximize the openings to reduce weight,
- fulfilling the structural strength requirements at the area with openings,
- avoid interference of opening with other equipment and systems (ventilation, lifesaving equipment, stairways, engine casing and other, etc)
- Cargo requirements (free height, type of cargo, etc.)
- Loading/unloading system for cargo (rampways, cargo doors, stowage etc.)

There are several configurations of open ro-ro cargo space, to be considered:

- Openings on both forward and aft ends with superstructure above
- Small garage forward with openings on the aft end and sides, large weather deck aft
- Large garage forward with openings on aft end and sides, small weather deck aft
- Large garage forward with openings on aft end where no openings on sides, small weather deck aft (note: not fulfilling the SOLAS Chapter II-1 Reg 3.35 requirements for open ro-ro cargo space)
- Open ro-ro cargo space where mooring equipment/deck is arranged in the cargo space. Covered poop deck or forecastle with open or closable mooring hatches, fairleads always open.
- Two levels of open roro decks, mainly on ro-ro cargo vessels.

Further, there are several arrangements with respect to the opening geometry at forward and aft ends of the open ro-ro cargo space, to be considered:

- Straight edge of deck above or alternative shapes
- Centre or offset casing
- Free height
- Cargo drive/parking patterns
- Need of crew passage during operation such as fire patrol or in emergency

Several configurations from existing ships are illustrated in the Appendix E and Appendix F.

6.3.2.1 Side openings closure aspects

If closure of the openings shall be arranged, the following shall be considered:

- additional weight
- system requirements (ventilation, etc)
- Installation cost

- ro-ro cargo space type
- Cargo restrictions (DG, loading/unloading operation, cargo capacity, etc)

Regarding the additional weight, permanent closing of side openings will lead to an increased weight due to structural and system (mainly ventilation) requirements, thus, increasing the lightweight of ship i.e. reducing the available deadweight and payload. The main additional weight items include steel for openings closure and additional ventilation ducts as well as additional ventilation system requirements (ventilators, cabling).

For example, closing side openings on the selected generic ship Stena Flavia would lead to an increased steel structural weight by approximate 27 tons and ventilation equipment weight of approximate 6 tons. This adds about 0.25% to lightweight and is 0,5% of deadweight.

Generally, the weight increase is higher on an existing vessel compared to a new vessel mainly because the adjustments to the existing structure and ship systems arrangement.

6.3.2.2 Aft and forward openings aspects

Aft and/or forward openings are usually arranged from side to side to allow free drive through the cargo space.

Closing of those openings will have direct impact on the design of the cargo space and cargo operation.

7 Methods

7.1 Simulation methodology

Main author of the chapter: Robert Svensson, RISE.

Computational Fluid Dynamic (CFD) simulations have been conducted with the software Fire Dynamics Simulator (FDS) [14]. FDS is appropriate for thermally driven flows with an emphasis on smoke and heat transport from fires in low-mach (Ma < 0.3) conditions [14]. The software is widely used in fire safety engineering and has been used in several other LASH FIRE tasks.

This chapter describes the background (design fires, scenarios, type of ventilation, loading conditions, wind conditions, etc.) to the FDS simulations carried out. The results of the simulations are presented in chapter 8.1 (natural ventilation) and 9.1 (mechanical ventilation).

7.1.1 Purpose of simulations and scenario description

Two sets of simulations have been conducted for this study; one set to study mechanical fire ventilation scenarios, and one set to study how the air quality/mixing of air in a naturally ventilated ro-ro space is affected by different opening percentages.

7.1.1.1 Natural ventilation in an open ro-ro space

FDS has been used to simulate the air exchange during normal conditions, i.e. no fire scenario, in an open ro-ro space with different opening percentages for the permanent openings. The purpose of the simulations for the air exchange in an open ro-ro space is to see how well the air is mixed in an open ro-ro space in comparison to a closed ro-ro space using mechanical ventilation on required capacity for 10 ACPH. By comparing the air exchanges in the open ro-ro space with the air exchange in the closed ro-ro space, it is possible to see what percentage results in a lower air exchange compared to the mechanical ventilation.

Different wind conditions have been tested for the open ro-ro space either representing a side wind or a frontal wind, as seen in Table 5.

Table 5: Simulated scenarios for air exchange simulations.

Ro-ro space type	**Ventilation**	**Speed**	**Openings**
Closed	10 ACPH, mechanical	0 knots	None
Open	2.5 m/s, side wind	0 knots	4 % side, aft open
Open	2.5 m/s, side wind	0 knots	10 % side, aft open
Open	7.5 m/s, side wind	0 knots	4 % side, aft open
Open	7.5 m/s, side wind	0 knots	10 % side, aft open
Open	8.23 m/s from the front	16 knots	4 % side, aft open
Open	8.23 m/s from the front	16 knots	10 % side, aft open

The side opening area has been chosen to either 10 % or 4 % of the side area. The 10 % value is chosen since it is the minimum opening area according to SOLAS definition of an open ro-ro-space, see 5.1.1. The 4 % value was chosen since it showed interesting results from earlier conducted tests in the RO5 project [15]. The model for the open ro-ro space is based on deck 4 of Stena Flavia.

7.1.1.2 Mechanical ventilation in a closed ro-ro space

The purpose of the simulations of the mechanical fire ventilation scenarios in a closed ro-ro space is to see the potential effects of using the mechanical ventilation in the early state of fire to improve the situation for the onboard firefighters to make a manual firefighting operation. These simulations have been mainly focused on investigating the steady state situation, with respect to visibility temperature, incident radiative heat flux and smoke layer height. The model for the closed ro-ro space is based on deck 3 of Stena Flavia. The fire has been set to 5 MW, representing one car burning. No fire propagation was simulated. No drencher was active. The ventilation has been either turned off, set to ordinary operation, or set to reversed operation, see Table 6 for simulated scenarios.

Table 6: Simulated scenarios for the use of mechanical ventilation in a fire scenario.

Scenario	Ventilation	Fire size	Fire position
1	Off	5 MW	fore
2	10 ACPH	5 MW	fore
3	8 ACPH reversed	5 MW	fore
4	16 ACPH reversed	5 MW	fore
5	Off	5 MW	centreline
6	10 ACPH	5 MW	centreline
7	8 ACPH reversed	5 MW	centreline

The simulation results were used to establish the distance from the fire where the critical values for these parameters are reached. By comparing the distance between the different mechanical fire ventilation scenarios, it is possible to evaluate if, and how, the usage of mechanical ventilation improves the possibilities to perform manual interventions in a closed ro-ro space.

FDS is badly suited for under ventilated simulations. In this study all scenarios will have a good amount of available oxygen during the investigated period. In the LASH FIRE report D11.1 [16], the total energy content based on the available oxygen in the closed Ro-Ro model was calculated to be 34 GJ. This could sustain a fire of 5 MW for approximately 2 hours.

7.1.1.3 Performance criteria

To investigate what effect the evaluated safety measures have on the conditions for manual firefighting, the three parameters temperature, incident radiative heat flux, and visibility were examined. There are different performance criteria in literature, further described here:

MSC/Circ.1002 on “Guidelines on Alternative Design and Arrangements for Fire Safety” [17], lists the following life safety performance criteria for the three above mentioned parameters:

- Maximum gas temperature: 60 °C;
- Maximum radiant heat flux: 2.5 kW/m^2; and
- Minimum visibility: 10 m or 5m in spaces ≤ 100 m^2.

The values from [17] are aimed at people without protective firefighting equipment. As firefighters onboard are expected to have protective equipment on during manual firefighting operations, the above values would be conservative to use. The values [17] are similar to the Swedish National Board of Housing, Building and Planning that provides the following tenability conditions levels for analysis of safe evacuation of buildings [18]:

- Maximum temperature: 80 °C
- Thermal radiation/radiant heat dosage: maximum 2,5 kW/m^2, or a brief dosage of maximum 10 kW/m^2 combined with maximum 60 kJ/m^2 in addition to the energy from a thermal radiation of 1 kW/m.
- Visibility: 10.0 m (in spaces > 100 m^2)

Like for IMO MSC circular MSC/Circ.1002, these values are aimed at people without protective firefighting equipment.

Runefors (2020) provides criteria for both with and without protective equipment (note that these values are based on shorter exposure times) [19]:

- Without protective equipment:
    - Temperature > 180 °C or radiant heat flux $\dot{q}''$ > 5 kW/m^2
- With protective equipment:
    - Temperature > 260 °C or radiant heat flux $\dot{q}''$ > 20 kW/m^2

In this study it is assumed that manual firefighting interventions in ro-ro spaces are made using with protective equipment.

The regulations for protective clothing for firefighter's onboard ro-ro ships currently allows fire suits with lower protective properties compared to the fire suits used on land [20]. In addition to this, the questions asked in this study assumes manual firefighting intervention for longer exposure periods than the short values used in [19]. Therefore, it is deemed most appropriate to use the critical values outlined in IMO MSC circular MSC/Circ.1002 [17]. These values will provide a conservative approach and allow consideration of an unprotected first responder.

The critical values further used for the three parameters examined in this study are summarized in Table 7 below.

Table 7: Critical values for the three examined parameters used in T11.14.

Parameter	**Critical value**
Temperature	60 °C
Incident radiative heat flux	2,5 kW/m^2
Visibility	10 m

7.1.2 Delimitations

Both simulations and tests were conducted without consideration of fire spread. Activation of drencher system or other extinguishing system was not included in this study.

The tests were carried out in a scale model of a ro-ro space. The tests can be used as basis for understanding fire behaviours and physics for different ventilation conditions. This is valid both regarding fire position and size, as well as natural and mechanical ventilation set-ups. The scaling, however, constitutes a limitation and the results should be viewed with this in mind.

7.1.3 Representation of a generic ship

The representation of generic open and closed ro-ro spaces was based on an existing ship, Stena Flavia. The ro-ro space modelled in the present study was based on the deck 3 and 4 of Stena Flavia with the help of the following documents provided by Stena Rederi AB:

- General Arrangement
- Fire Control Plan
- Open ro-ro space General Arrangement.
- Vehicle Deck Ventilation

Figure *5* presents the general arrangement of deck 3 and 4.

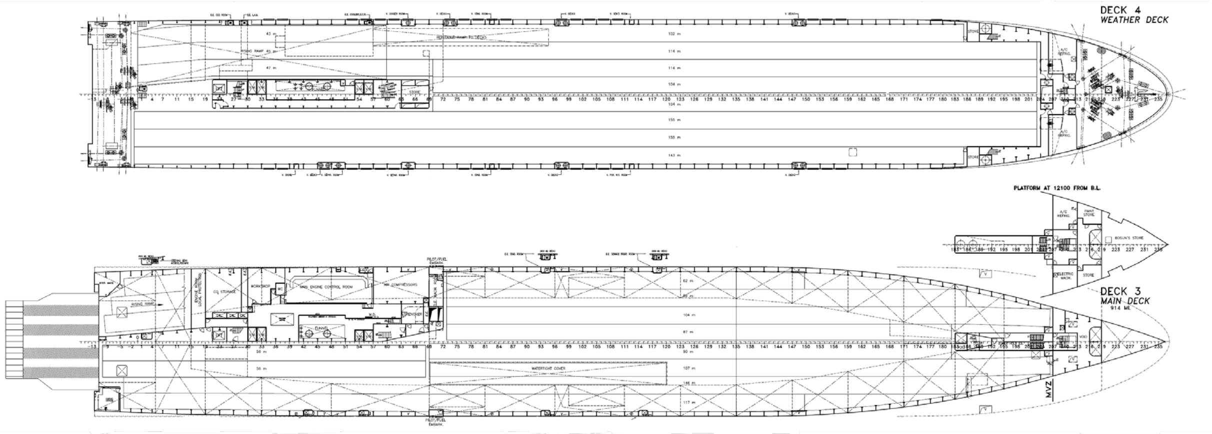


Figure 5: Deck 3 (lower) and 4 (upper) of the Stena Flavia.

7.1.4 FDS model

It was decided for the present study to use two types of ro-ro spaces, a closed ro-ro space with no openings, and an open ro-ro space, based on decks 3 and 4 of Stena Flavia, respectively.

The closed ro-ro space had the following inner dimensions:

- 162 m long
- 25.6 m wide
- 5.8 m high.

The model used in the mechanical ventilation simulations can be seen in Figure *6* and Figure 7. The aft is to the left and the front is to the right of the figures.

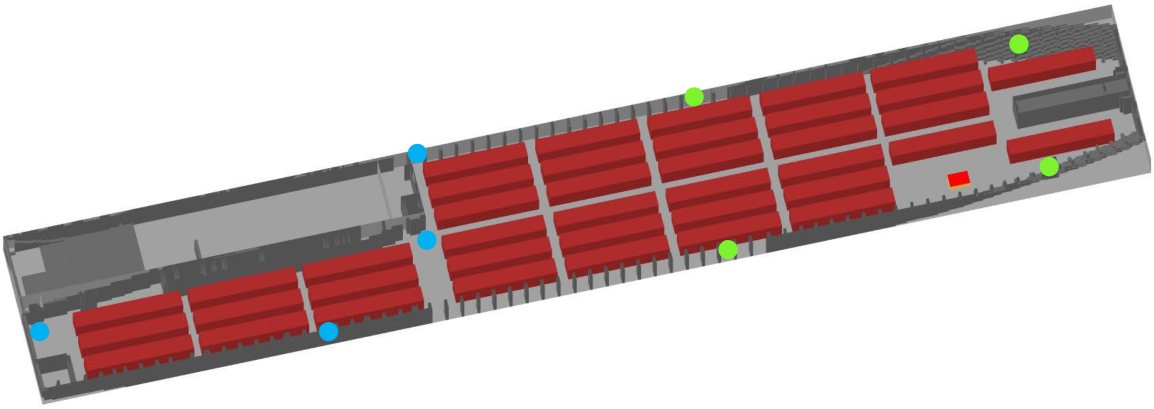


Figure 6: Closed ro-ro space based on STENA Flavia, deck 3. Green dots mark the positions of supply fans and blue dots mark the positions of the exhaust fans. The red area close to the front is the fire source for scenarios 1-4. The rectangular boxes represent trucks. The ceiling beam framework was represented but is hidden in the picture.

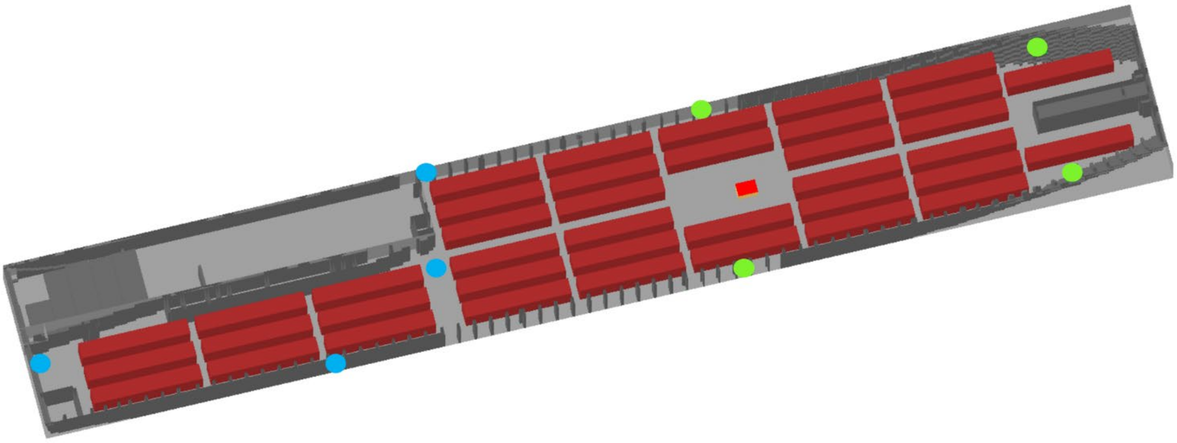


Figure 7: Closed ro-ro space based on STENA Flavia, deck 3. Green dots mark the positions of supply fans and blue dots mark the positions of the exhaust fans. The red area close to the middle is the fire source for scenarios 5-7. The rectangular boxes represent trucks. The ceiling beam framework was represented but is hidden in the picture.

The open ro-ro space (deck 4) for the natural ventilation simulations had the following inner dimensions:

- 156 m long
- 25.6 m wide
- 6 m high.

The model used for the natural ventilation simulations can be seen in Figure 8 and Figure 9. These simulations were simulated without a fire. It is to be noted that the actual configuration of openings on Stena Flavia has been modified in the model. Stena Flavia has an opening percentage of 13% on deck 4. In the model, the opening percentage was reduced to 10% to align with the definition for open ro-ro spaces.

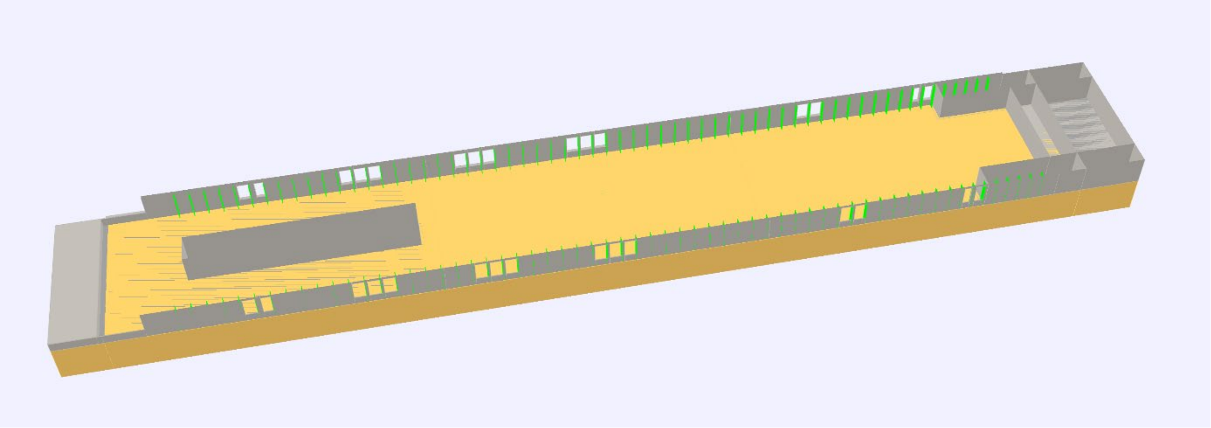


Figure 8: Open ro-ro space based on STENA Flavia deck 4. There is no present fire source or cargo in the air exchange simulations. The framework in the ceiling is hidden in the picture. The area of the side openings is 10 % of the total side area.

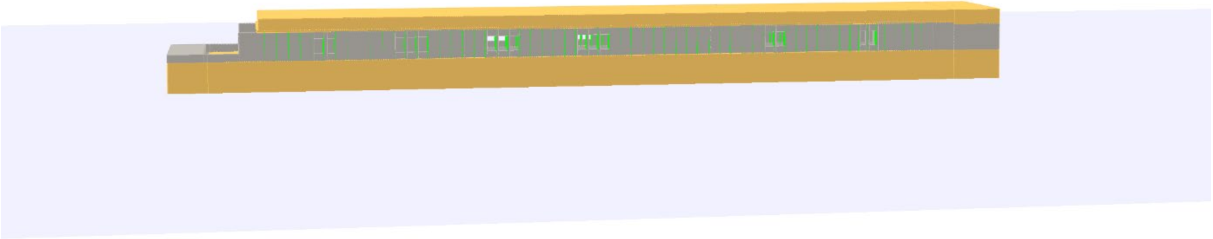


Figure 9: Sideview of closed ro-ro space. The outer geometry is simplified, and box like in comparison to the actual ship. The side openings of the ship can be seen in the picture. The area of the side openings is 10 % of the total side area.

7.1.4.1 Domain and discretization

The numerical grid of computational cells in the FDS software is rectilinear and constrains the geometry to follow this grid. Closest to the fire source (<10 m in all directions), the computational cells are 20 cm in all directions. Outside of this volume, the largest cells within open and closed ro-ro spaces were 40 cm x 40 cm x 20 cm. For the open ro-ro space model, with the outdoor geometry, the largest cells furthest away from the ship was 3.2 m in all directions. The volume outside of the open ro-ro space extends a few hundred meters around the model of the ship (length x width x height is 768 m x 377.6 m x 76.8), see Figure 10

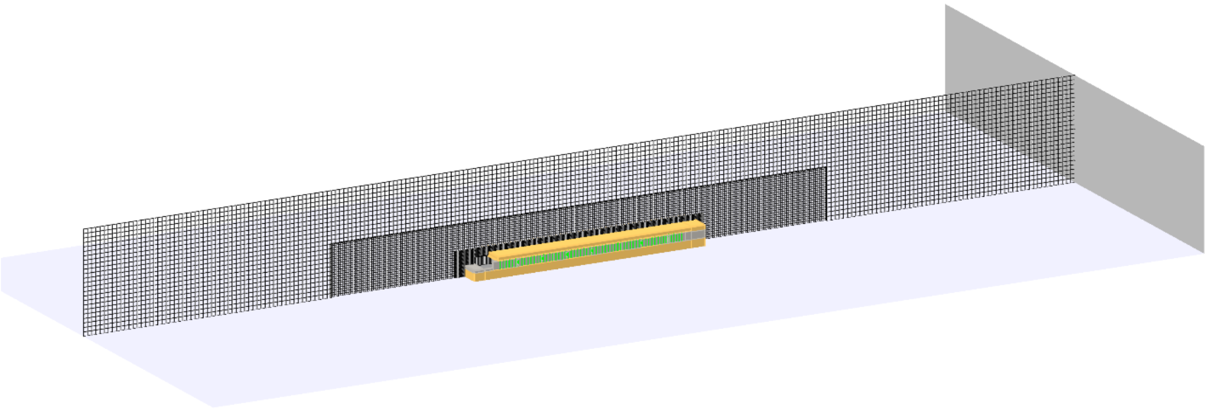


Figure 10: Domain outside of open ro-ro space.

The grid resolution is recommended to have a ratio of at least 10 < $D^*/\delta\mathrm{x}$ < 20 [14] where δx is the grid size and D^* is the characteristic fire diameter defined according to equation (1).

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{g}}\right)^{2/5} \qquad (1)$$

Where $\dot{Q}$ is the heat release rate [W], ρ_∞ is the ambient density of air [kg/m^3], $C_p$is the specific heat capacity of air [J/kgK], T_∞ is the ambient temperature [K], and g is the gravitational acceleration.

For a 5 MW fire $D^*/\delta\mathrm{x} = 9.2$, which is below the recommended resolution. A grid refinement study was made and the resolution of 20 cm in all direction was considered good for the purpose of this study and was therefore chosen. The comparing study was investigating resolutions closest to the fire source of either 10 cm, 20 cm, or 40 cm (40 x 40 x 29 cm) cells. The comparison of light extinction coefficient due to smoke for the different resolutions can be seen in Figure 11 and Figure 12. A comparison of temperatures for the different resolutions can be seen in Figure 13 and Figure 14.

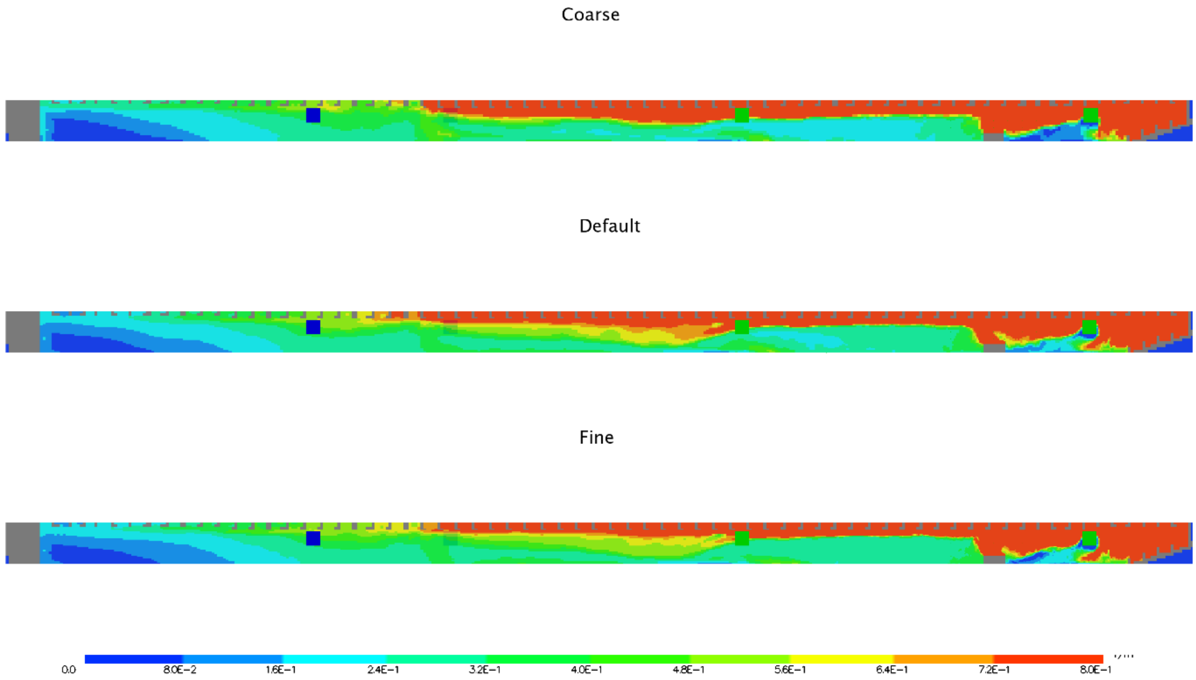


Figure 11: Comparison of light extinction coefficient after 4 min fire for three different grid resolutions. The picture shows a vertical plane cut through the 5 MW fire source, seen as a grey box far to the right.

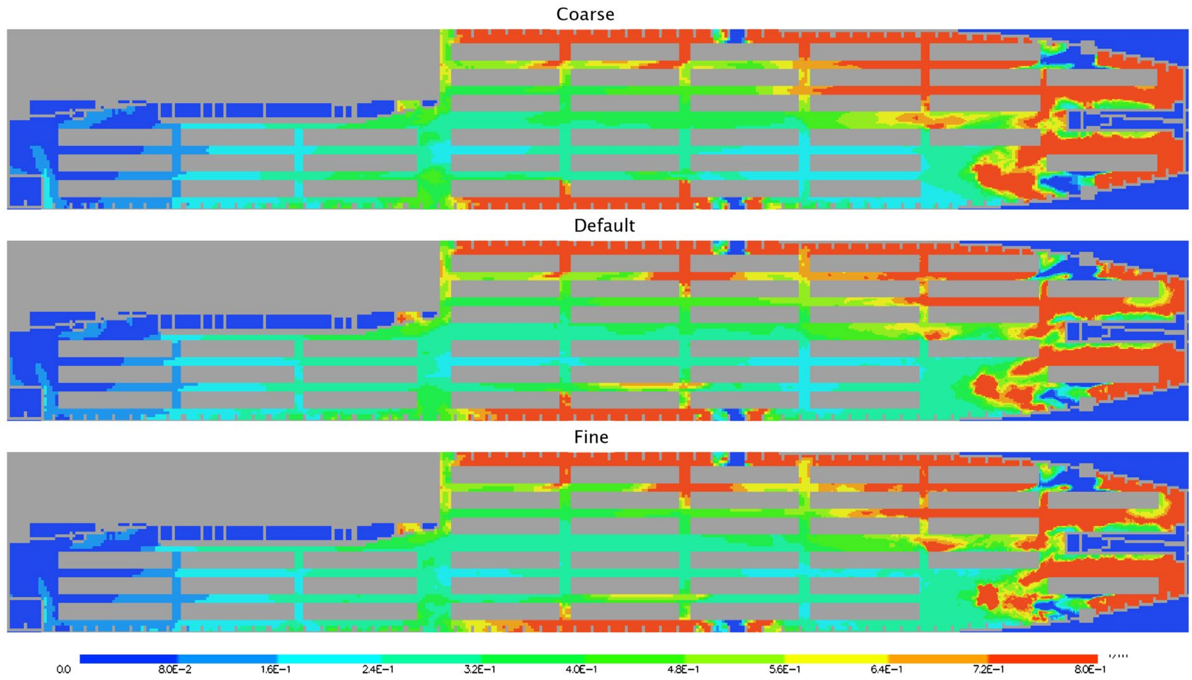


Figure 12: Comparison of light extinction coefficient after 4 min fire for three different grid resolutions. The picture shows a horizontal plane cut at 1.9 m above deck.

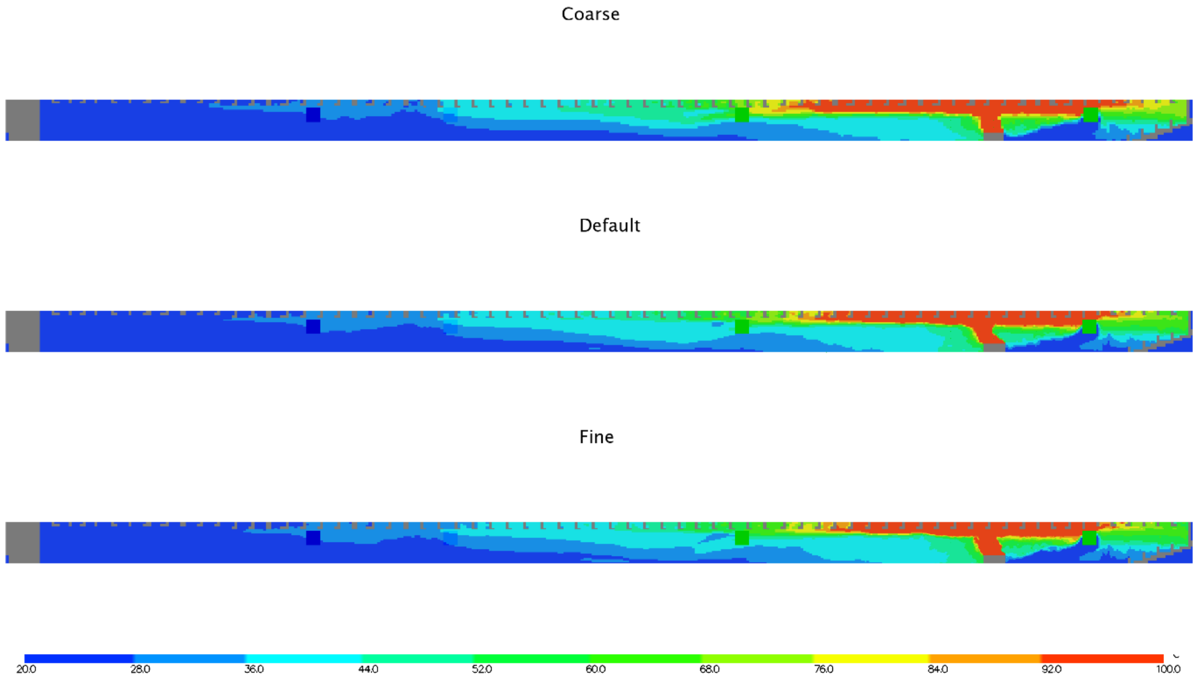


Figure 13: Comparison of temperature after 4 min fire for three different grid resolutions. The picture shows a vertical plane cut through the 5 MW fire source, seen as a grey box far to the right.

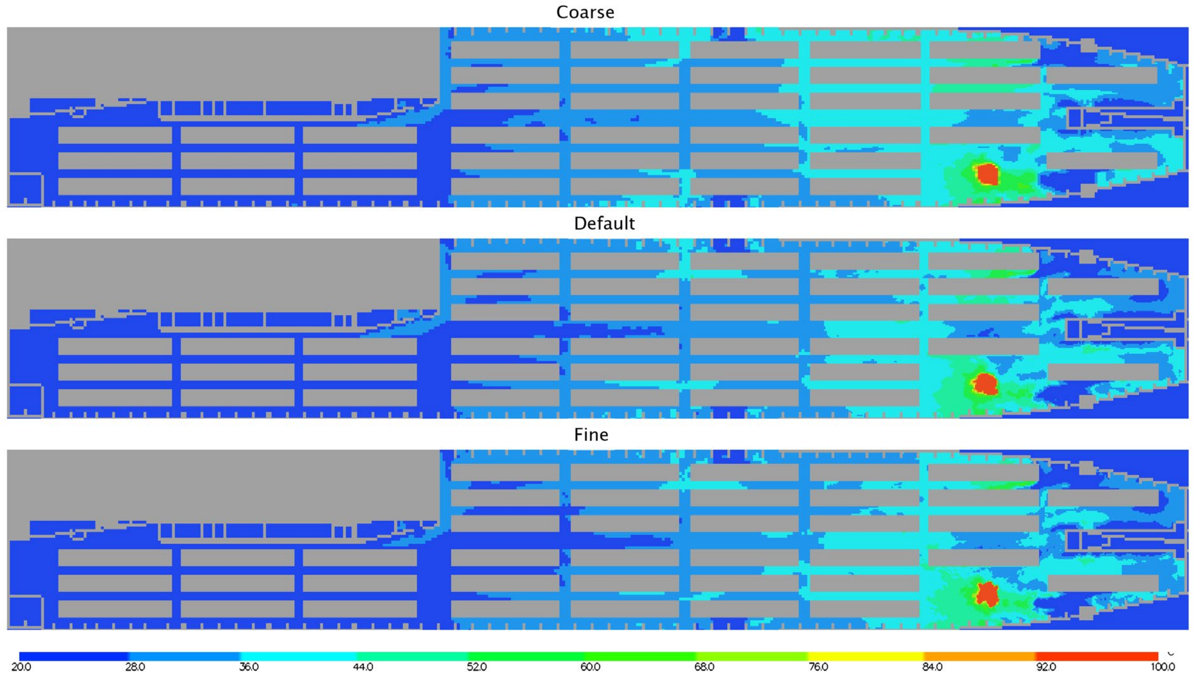


Figure 14: Comparison of temperature after 4 min fire for three different grid resolutions. The picture shows a horizontal plane cut at 1.9 m above deck.

7.1.4.2 Cargo

The cargo for the mechanical ventilation simulations has been chosen to be trucks. The trucks are represented as boxes with the dimensions 15.6 m x 2.4 m x 3.2 m and are hovering 0.8 m above the floor. There is a 1 m distance from the top of the boxes to the longitudinal and transversal beams in the ceiling. The boxes are adiabatic, so they exchange no energy with their environment. There has been placed a total of 39 trucks in the closed ro-ro space. The volume of the trucks fills up 23 % of the total volume. The trucks are distributed to 6 lanes in comparison to the existing 8 lanes on the ship. The reason for the reduction of lanes is to slightly widen the flue spaces between the trucks to avoid numerical instability.

For the natural ventilation simulations of air exchange there is no cargo at all.

7.1.4.3 Material properties

All surfaces constituting the ro-ro space were assumed to be steel with a thickness of 10 mm. Steel properties were taken from the Eurocode 3 [21] and are presented in Table 8. The heat capacity was then modified down to 10 % of the actual value to quicker reach a steady state in the simulation.

Table 8: Steel properties according to Eurocode 3.

Emissivity (-)	0.7
Density (kg/m^3)	7850
Specific heat (J/kg.K)	$450 + 0.28 \cdot T_s - 2.91 \cdot 10^{-4} \cdot T_s^2 + 1.34 \cdot 10^{-7} \cdot T_s^3$
Conductivity (W/m.K)	$14.6 + 1.27 \cdot 10^{-2} \cdot T_s$

T_s represents the temperature of the steel in Celsius.

The ceiling has been insulated in the models of both decks to fulfil A-60 performance.

The A class division deck are in accordance with the documents provided by Stena Rederi AB and consists of standard thermal insulation certified for A-60 performance.

Regarding the properties of the thermal insulation, they were taken from the manufacturers and are presented in Table 9. The heat capacity for the insulation have also been tuned down to only 10 % of the value in the table to quicker reach a steady state situation.

Table 9: Thermal insulation properties.

Material property		**A-60**
Thickness (cm)		7
Emissivity (-)		0.7
Density (kg/m^3)		56
Specific heat (kJ/kg·K)	T_i =100	0.84
	T_i =400	1.154
	T_i =600	1.212
	T_i =700	1.586
Conductivity (W/m·K)	T_i =10	0.031
	T_i =100	0.041
	T_i =200	0.057
	T_i =550	0.18
	T_i =650	0.22
	T_i =700	0.23

T_i represents the temperature of the thermal insulation in Celsius.

7.1.4.4 Mechanical ventilation for a closed ro-ro space

For the closed ro-ro space, the model is a closed volume with eight pressure dependent fans, four supply fans in the front and 4 exhaust fans in the rear. The volume flow is dependent on the pressure difference between the ambient pressure outside of the model and the pressure closest to the fan positions in the model, see Figure 15. During normal operation at ambient pressure without a fire in the model, the total volume flow in the model will be close to 10 air changes per hour (ACPH) according to documents from Stena Teknik. The closed space has been simulated without ventilation, normal operation (10 ACPH), reverse operation with 8 ACPH (80 % of full capacity in reverse, based on discussions with WP05), and reverse operation with 16 ACPH.

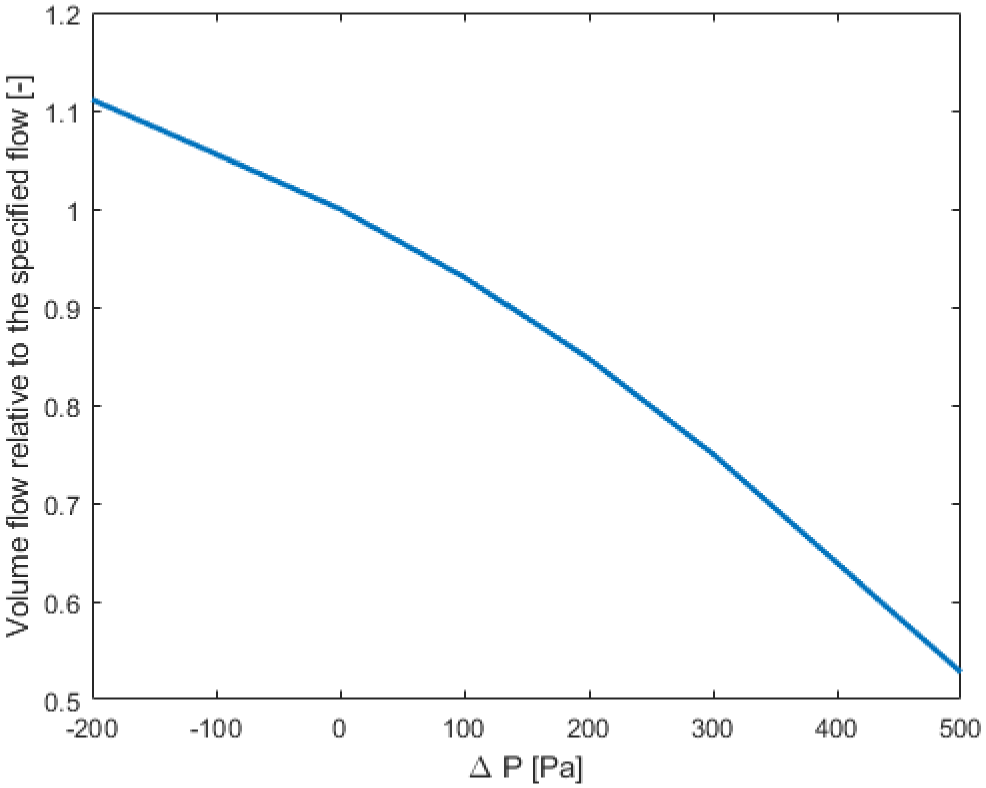


Figure 15: Fan curve used for simulations of closed ro-ro space. The expected aerodynamic resistance from the HVAC system is subtracted from curve so the pressure difference is between the inside of ambient pressure outside the model and the pressure closest to the fan position in the model.

7.1.4.5 Natural ventilation for an open ro-ro space

For the open ro-ro space, the aft of the deck is open. On the sides of the deck there are several openings with dimensions 1.9 m X 3.2 m with a total open area equivalent to 10 % or 4 % of the side area up to furthest point of the loadable volume. The ventilation has been created by either having no side wind and only a frontal wind equivalent to the traveling speed of the ship or having a side wind perpendicular to the ship.

The side wind was chosen to 7.5 m/s or 2.5 m/s, where 7.5 m/s is the average wind speed on the Baltic Sea [22] [23]. The wind profile depending on height above the see level can be calculated according to:

$$u = u_0 \left(\frac{z}{z_0}\right)^p \tag{2}$$

where u is the wind velocity [m/s] at height z above sea level [m], u_0 is the reference wind velocity defined at a height z_0 (set to 10 m), and p is 0.13, which is the same value as used for example by Rahimpour and Oshkai [24]. The resulting wind speeds can be seen in Figure 16.

The computational domain was extended to be 768 m x 377.6 m x 76.8 m in order to let the wind profile stabilize before reaching the ship. The top of the domain was given a free-slip boundary condition (non-penetrable wall with no friction). The ship is blocking less than 5 % of the cross-section area of the domain, and the sides of the domain were set to a zero-gradient boundary condition. The representative wind and numerical approach were developed for simulations presented in D09.2 “Developed ro-ro spaces fire detection solutions and recommendations “ [25].

The frontal wind scenarios is supposed to imitate a case where there is no wind but the ship is moving. For this imitation the wind profile is constant in relation to the height above see level and both the top and the bottom of the domain has a free-slip condition. The speeds have been set to either 2.6 m/s (5 knots) or 8.2 m/s (16 knots).

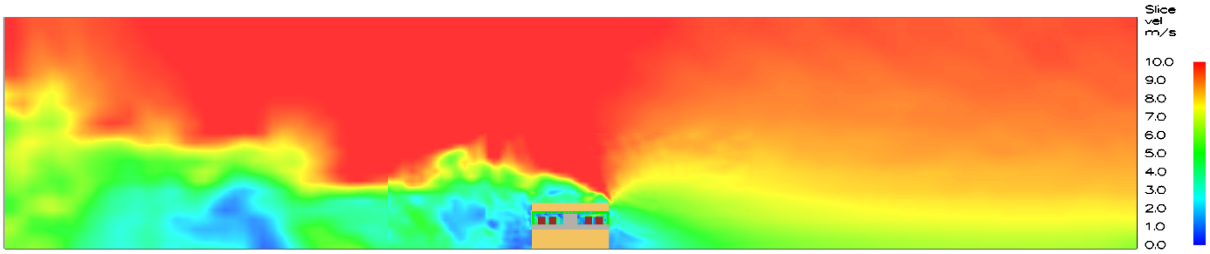


Figure 16: Wind speeds in a view from the rear of the ship. The wind is traveling from the right to the left with a speed of 7.5 m/s at 10 m above sea level. Total hight shown in the figure is 76.8 m.

7.1.4.6 Modelling of the fire

The fire source for the mechanical ventilation scenarios have been chosen to represent an early-stage ro-ro space fire. The heat release rate (HRR) is set to a constant of 5 MW, which is expected to represent a fully developed car fire [26], [27]. For any scenario with mechanical ventilation, only the eventual steady state has been studied. The fuel is set to be N-heptane with an energy of combustion of 48 MJ/kg. The soot yield is set to 6 % of the fuel weight and the CO-yield to 10 % [11]. This results in a soot supply of 7.4 g/s into the simulation domain.

The 5 MW car fire should have a good supply of oxygen in the closed ro-ro space for the purpose of this study. For the closed ro-ro space, the total volume of the space without cargo was approximately 20 000 m^3. If it is assumed that all oxygen is consumed from the ambient volume fraction of 21 % oxygen in air down to 11 %, and an energy release of 13.1 MJ per consumed kg of air, the total energy released would be 34 GJ. With the fans on and a ventilation of 10 ACPH, the oxygen could sustain a fire with an HRR of approximately 100 MW. If the ventilation is turned off and the space is completely shut the air could theoretically supply a 5 MW fire with air for approximately two hours.

The fire source was set to an area elevated 1.2 m above the deck with the dimensions 3 m x 2 m. The area is selected to give a realistic maximum heat release rate per unit area (HRRPUA) of 833 kW/m^2. The source has been placed either 2/3 of the ship length to the front along the centreline or in the front on the starboard side.

7.1.4.7 FDS virtual sensors

The simulations are studied by investigating data saved in either slice files or devices saved in FDS. The slices are data saved in horizontal planes at heights of either 1.9 m or 2.9 m (half the ceiling height) above the deck or in vertical planes cutting through the fire source. For the slices, the temperatures and light extinction coefficient were investigated. Devices have been used in FDS to save a time resolved property at a certain position over time. The temperature, light extinction, and incident radiative heat flux have been monitored at 1.9 m and 2.9 m above deck with 2 m spacing in x- and y-direction. The radiation is measured as a surface facing upwards.

7.1.4.8 Determining the air exchange for the open ro-ro space

In order to determine and compare the air exchange between different wind scenarios and opening areas the air has been tracked. All the air that was originally contained within the deck at the start of the simulation, when the fans are activated, has been separately monitored from the rest of the air.

The air initially contained within the volume of the deck has then been integrated over time, to see how much of it have been extracted. As a reference, 10 ACPH should correspond to that half the air would be extracted in 180 s.

All the air exchange simulations have been made without any cargo on deck. The simulations are done without any fire present.

7.2 Model scale test methodology

Main author of the chapter: Sebastian Norén, RISE.

The model scale tests were performed in RISE fire hall test facility in Borås, Sweden.

Using model scale experiments is an effective way to obtain answers concerning growth and spread of fires. The scaling technique has been used in previous studies for the same type of geometry [28] [29]. Compared to full scale tests with a very large space there are advantages with scaling. It can be lower costs and improved feasibility to perform the tests. Using model scale tests means that scaling laws need to be used to scale up the results from the model to the full scale, see 7.2.1.

Two separate test series were carried out: one for natural ventilation and one for mechanical ventilation.

The main purpose with the natural ventilation test series was to investigate and quantify the impact on the fire development when varying the configuration of the side openings for natural ventilation in an open ro-ro space. In total, eight tests were performed in the natural ventilation test series, including two free burning tests under a hood calorimeter. The natural ventilation test series was focused on large fires (a worst-case scenario) when drencher system and ventilation system were not operated. The mechanical ventilation test series was only focused on relatively small fires in order to simulate conditions where active firefighting actions were possible.

The main purpose with the mechanical ventilation test series was to quantify and study the effects of mechanical ventilation on the fire development in a closed ro-ro space, using reversible fans as a means of smoke ventilation management. In total, 14 tests were performed in the mechanical ventilation test series, including two free burning tests under a hood calorimeter.

The fire hall facility is 18 m wide, 22.3 m long and has a height of 20 m. The model was placed inside the test hall. In the following sections the test set-up as well as model and test procedures will be described.

7.2.1 Scaling laws

The scaling correlations used in these model scale tests are based on the Froude modelling and are the same used in the RO5 [1] study and in a previous study by Larsson et al., [29]. The scaling laws are summarized in Table 10.

Table 10: Scaling correlations used in this LASH FIRE study, T11.14.

Quantity	**Scaling law***	**Equation**
Time	$\frac{t_M}{t_F} = \sqrt{\frac{L_M}{L_F}}$	*Equation 1*
Velocity	$\frac{u_M}{u_F} = \sqrt{\frac{L_M}{L_F}}$	*Equation 2*

Fire size	$\frac{Q_M}{Q_F} = \left(\frac{L_M}{L_F}\right)^{5/2}$	*Equation 3*
Gas temperature	$T_M = T_F$	*Equation 4*
Ventilation Rate	$\frac{V_M}{V_F} = \left(\frac{L_M}{L_F}\right)^{5/2}$	*Equation 5*
Air Change Per Hour	$\frac{ACPH_M}{ACPH_F} = \left(\frac{L_M}{L_F}\right)^{-1/2}$	*Equation 6*
Heat flux	$\frac{\ddot{q}_M}{\ddot{q}_F} = \sqrt{\frac{L_M}{L_F}}$	*Equation 7*
Thermal inertia	$\frac{(k\rho c)_{s,M}}{(k\rho c)_{s,F}} = \left(\frac{L_M}{L_F}\right)^{\frac{3}{2}}$	*Equation 8*
Thickness	$\frac{\left(\frac{k}{\delta}\right)_{s,M}}{\left(\frac{k}{\delta}\right)_{s,F}} = \sqrt{\frac{L_M}{L_F}}$	*Equation 9*

*Explanation for the table: Subscript (M) = Model, (F) = large scale, → $(L_M = 1;\ L_F = 8)$

7.2.2 Radiation calculations

The radiation was calculated using Equation 10 [30].

$$\dot{q}''_{inc} = \sigma T_{PT}^4 + \frac{(h + K_{PT})(T_{PT} - T_\infty) + C_{PT}\frac{dT_{PT}}{dt}}{\varepsilon_{PT}}$$

Equation 10

With:

T_{PT} = temperature of PT at time t

T_∞ = temperature of nearby thermocouple at time t

K_{PT} = 8 W/m^{2}K

C_{PT} = 4200 J/m^{2}K

h = 12 W/m^{2}K

7.2.3 The model

The model is built in scale 1:8 to represent a ro-ro space on a vessel. The overall dimensions of the model were: 14.4 m long, 2.8 m wide and 0.6 m high which in large scale represents: 115.2 m long, 22.4 m wide and 4.8 high.

The model is constructed of 9 sections of 1.5 m and 1 section of 0.9 m. An overview of the model is shown in Figure 17 below. As for the previously conducted tests [1], the model was placed on a supporting system to achieve a better work environment for the technicians constructing the model, as well as the opportunity to study the fire and smoke development inside the model.

Figure 17: The model of the ro-ro space was built up in the fire hall in Borås. Section 1 is in the bottom left of the figure, and Section 10 is in the top right of the figure.

The model was constructed of steel with a thickness of 1.5 mm and was covered with 6 mm gypsum board to even out the gas temperature on the inside. The model was fitted with “beams” inside in the transverse direction and the longitudinal direction of the model, see Figure 18.

Figure 18: Photo from inside model. Beams are visible on side and in deckhead.

The distance between the beams in the transverse direction ranges between 0.29 and 0.32 m (corresponding to approx. 2.3 – 2.55 m), with exception to section joints 4-5 which has 0.24 m distance. The distance between the beams in the longitudinal direction is 0.7 m (corresponding to approx. 5.6 m in full scale).

The short ends of the model were open or closed with a steel plate depending on the scenario. The closures were mounted on the model with bolts and screws for the closed scenario. Ceramic insulation was used between the sections to keep the model as tight as possible. Openings made on the long sides of the model and fan positions are further described in section 7.2.3.1.

A hatch was constructed at the bottom plate of the model, located in the centre of the model, to be able to visually inspect the model's inside and to change the fire source prior to each test.

An illustration of the sectioning, from 1 to 10, of the model is shown in Figure 19.

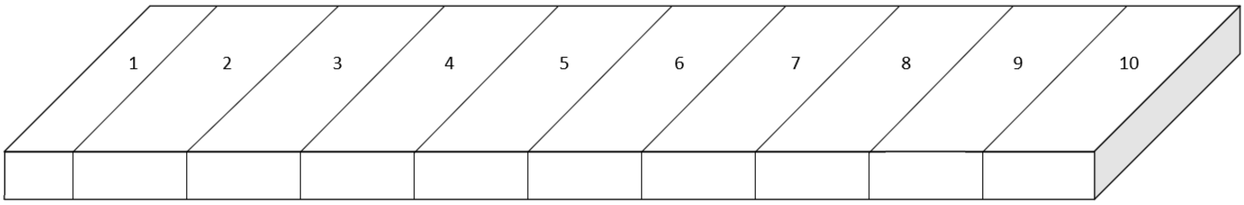


Figure 19: The model divided into sections from 1 to 10.

The model was used for both test series and is further described in the following sections.

7.2.3.1 Natural ventilation

Open ro-ro spaces are according to SOLAS II-2/3.35 *"those ro-ro spaces that 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."*

The interpretation used in this project is that the side plating (long side walls) of the model should be at least 10% open. The summarized area of the long sides is 17.28 m^2 (14.4*0.6*2) and the position and dimensions of the two different opening configurations can be seen in Figure 20.

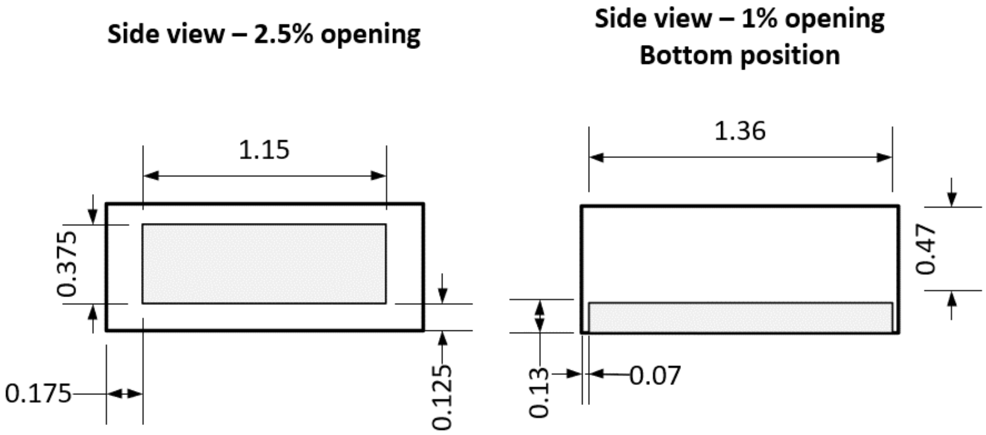


Figure 20: Openings marked in grey. The side view with 2.5% opening was used only for the reference scenario 1-1, for all other scenarios, side view – 1% opening, bottom position was used.

In the test scenarios, the 2.5% opening configuration was only used for the first test as a reference to previous research done in the RO5 project [1], in which sections 4 and 8 were equipped with these openings. For the remaining natural ventilation test scenarios, the distribution of the openings along the ship sides was varied between an even distribution and a compact distribution. For the compact distribution, the openings were concentrated near the short ends of the model, leaving the middle section closed. The compact distribution is illustrated in Figure 21 where sections marked with a cross were used for low positioned openings (approximately 0.13 cm high openings). For the even distribution, openings were made in sections 2, 4, 6, 8 and 10 which can be seen in Figure 22.

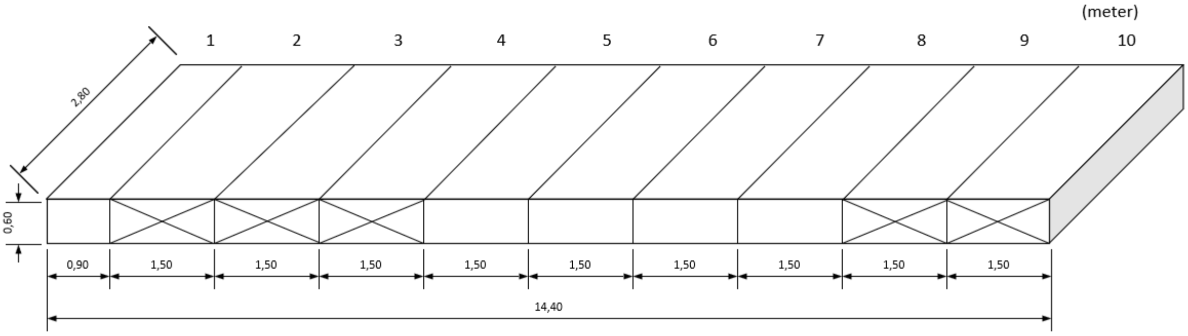


Figure 21: View of the model that was used in the model scale tests, with compact distribution of the openings (open sections marked with X). Marked sections were open on both sides of the model.

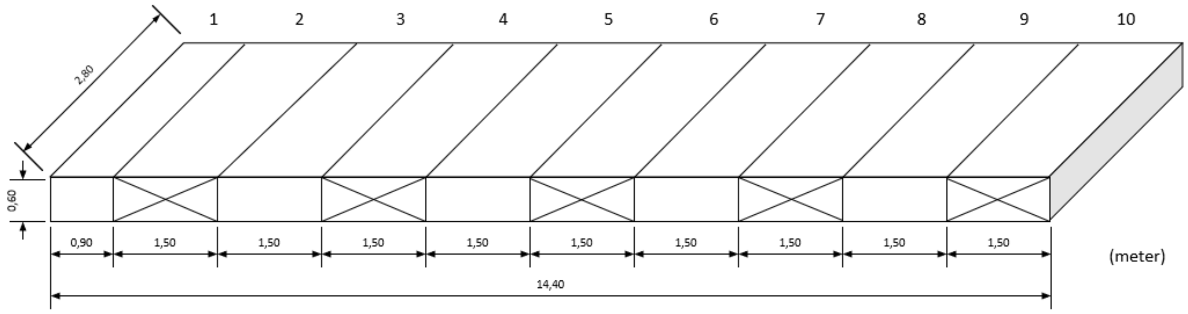


Figure 22: View of the model that was used in the model scale tests, with even distribution of the openings (open sections marked with X). Marked sections were open on both sides of the model.

7.2.3.1.1 Fire source

Two different fire sources were used in the tests, heptane in a steel tray and wood crib. Each test series had a main fuel and a secondary fuel. The secondary fuel was used for sensitivity check. For natural ventilation wood was used as an alternative fuel as a sensitivity check for the heptane fuel.

For natural ventilation, the main fire source was heptane. Wood was used as an alternative fuel as a sensitivity check for the heptane fuel.

For natural ventilation, the fire sources were calculated to a theoretical size of 400 kW, equivalent to approximately 70 MW in large scale. The two fire sources are shown in Figure 23.

Figure 23: Larger wood crib fire source (left) and larger heptane fire source (right) for natural ventilation tests.

For natural ventilation, the wood crib fire source was built of wooden studs with dimension 45 * 45 mm and with a total length, width, and height of 1.2 * 0.45 * 0.315 m. The heptane fire source was circular tray with diameter 0.59 m. The tray was filled with 27 litres of heptane for each test.

For natural ventilation test series, the fire source was always placed in the middle of the model, at 7.65 m from the start of section 1.

Free burning tests were conducted before the test scenarios with both fire sources.

7.2.3.1.2 Instrumentation and documentation

All tests were documented with photographs and with four video cameras from different angles inside the fire hall.

Gas temperature, steel temperature, fuel mass loss, gases (CO, CO_2, O_2), air flow in openings, radiation, and light transmission through smoke were measured during the tests. Gas and steel temperatures were measured using welded K-type thermocouples (TC). Plate thermocouples were used to analyse radiation.

Figure 24 is introducing the symbols used in Figure 25 and Figure 26 which show the location of the instrumentation, side view and top view, for the natural ventilation tests.

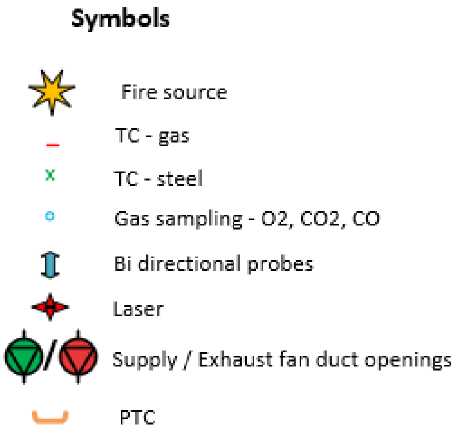


Figure 24: Instrumentation symbols.

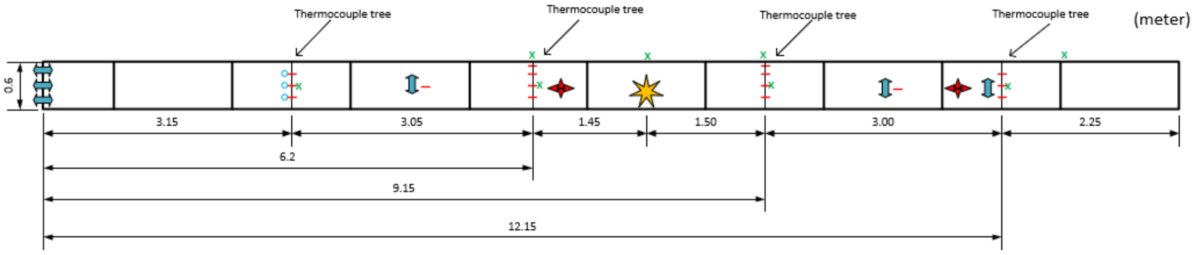


Figure 25: Side view of the model with instrumentation for natural ventilation tests. Section 1 is furthest to the left, and Section 10 is furthest to the right.

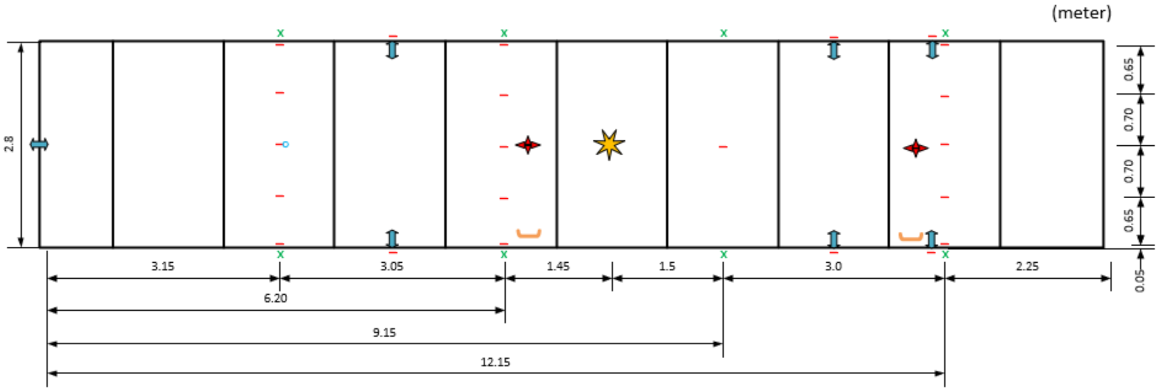


Figure 26: Top view of the model with instrumentation for natural ventilation tests. Section 1 is furthest to the left, and Section 10 is furthest to the right.

The gas temperatures inside the model were measured using vertical and horizontal thermocouple (TC- 0.5 mm diameter, type K) trees. The thermocouples close to the fire source were shielded 1.5 mm type K in order to withstand the high gas temperatures. The vertical trees were placed as follows:

- at 6.2 m and 9.15 m measured from start of section 1, located 0.05, 0.15, 0.30 and 0.45 m from the inner roof.
- at 3.15 m and 12.15 m measured from start of section 1, located 0.15, 0.30 and 0.45 m from the inner roof.

The horizontal thermocouple trees were placed at 3.15, 6.2 and 12.15 measured from start of section 1. They were located at 0.05, 0.7, 2.1, 2.75 m from the side plating and at a height of 0.3 m from the roof.

Plate thermocouples, PTs, were placed 6.73 and 12.0 m measured from start of section 1.

The thermocouples measuring the steel temperature were placed on the outside of the model on top of the upper deck and on the sides. 0.5 mm welded K-type thermocouples were used for this purpose. Thermocouples on deck were located at 6.2 m, 7.65 m, 9.15 m, and 12.95 m, respectively, measured from start of section 1. The thermocouples on the sides were located at 3.15 m, 6.2 m, 9.15 m, and 12.15 m, respectively, measured from start of section 1.

CO, CO_2, O_2 sampling points were placed at 3.20 m measured from start of section 1 and located 0.15, 0.3 and 0.45 m from the inner roof for the natural ventilation tests.

Light transmission was measured using laser and was placed in section 5 at 6.83 m from start of section 1, and in section 9 at 12.1 m from start section 1, both located 0.37 meters from the inner roof.

Bi-directional (BD) probes were used to measure the flow in the openings, placed in the centre of two openings on each side, either in section 4 and 8 or section 4 and 9, depending on the opening configuration. Three probes were also placed in the open short end located 0.21, 0.37 and 0.52 m, respectively, from the inner roof. The main purpose was to control air flow direction during test, and the result are not presented in this report.

HRR was calculated with measurement of mass loss using the weighing platform, as described in section 7.3.1.

7.2.3.2 Mechanical ventilation

SOLAS II-2/20.3 is titled "*Precaution against ignition of flammable vapours in closed vehicle spaces, closed ro-ro spaces and special category spaces*". The mechanical ventilation in closed ro-ro spaces is today designed so that it fulfils the SOLAS II-2/20.3.1.1 requirement of capacity of 6 or 10 air changes per hour (ACPH) depending on the type of ship and type of space. In closed ro-ro space onboard a ro-pax it is required to be 10 ACPH.

To represent the mechanical ventilation in the built-up ro-ro deck (the model) in the test scenarios two supply fans and two exhaust fans were used. The fans were used to test different ventilation constellations with both supply and exhaust air from the inside of the model. The four fans were controlled by a frequency converter and could achieve capacities up to 20 ACPH depending on the scenario. The theoretical volume of the model was 24.192 m^3.

The fans were divided into two supply and two exhaust fans. The exhaust fans had a volume flow of 0.095 m^3/s, i.e., total of 0.19 m^3/s for both. The supply ducts were located on the end of section 1 and on the right side in section 4 when seeing the model from section 1. The exhaust ducts were symmetrically placed on the left side in section 8 and on the short end of section 10. The fan duct positions are visualized in Figure 27.

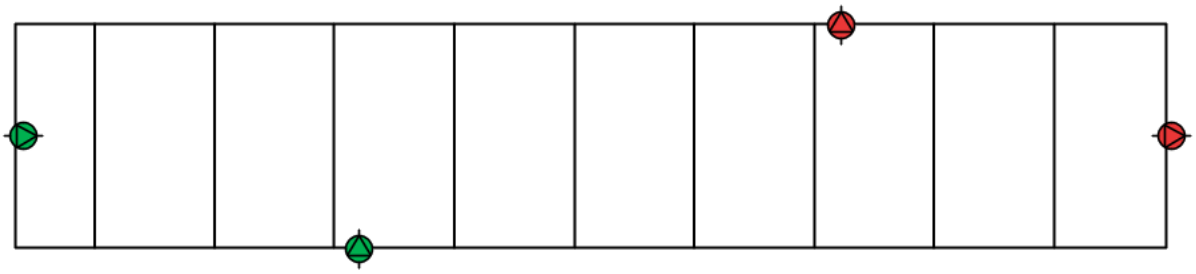


Figure 27: Supply and exhaust duct positions. The green fans are supply and red fans are exhaust.

Positions of the inlet and outlet ducts in the respective sections are visualized in Figure 28.

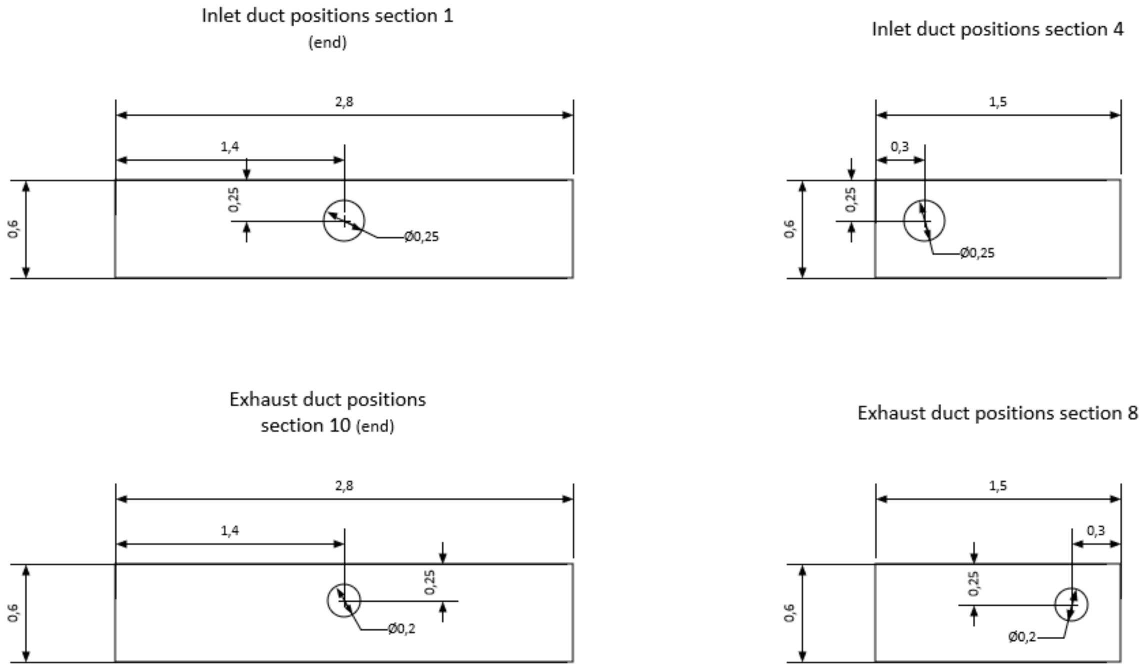


Figure 28: Exact positions of the inlet and outlet ducts in the respective sections.

The supply duct diameters were ramped down from 0.3 m to 0.25 m and two meshes were mounted in each of the inlet ducts, one being situated directly after the fan and one where the air enters the model, to distribute the flow more homogenously. The length of the supply ducts were approximately 3 meters and the exhaust ducts approximately 21.5 meters.

A bi-directional (BD) probe was mounted in the centre of all four ducts to be able to monitor and adjust the flow accordingly. The BD probes were mounted one meter from the inlet into the model for the supply duct in section 4 and one meter ahead of the bend in section 1. For the exhaust ducts, the BD probes were mounted on a straight part with at least one meter of straight duct in both directions. To achieve a more accurate measurement of the average velocity in the ducts, a flow coefficient of 0.817 was used and multiplied with the measured velocity [31]. The flow profile in a duct is not uniform due to the boundary layer and for small Reynolds numbers the boundary layer can be rather significant. The supply fan in section 4 is shown in Figure 29.

Figure 29: Supply fan in section 4.

The outlet duct diameters were 0.2 m and did not have any meshes inside. The outlet ducts were routed with an equal length of approximately 21 meters into a small hood colleting the gases and calculating the heat release rate (HRR) based on the oxygen consumption measured by the extraction. The outlet duct can be seen in Figure 30.

Figure 30: Duct from the model to the hood for measurement of HRR. Exhaust fan in section 8 (closest).

7.2.3.2.1 Fire source

Two different fire sources were used in the tests, heptane in a steel tray and wood crib. Each test series had a main fuel and a secondary fuel. The secondary fuel was used for sensitivity check. For mechanical ventilation, the main fuel was wood. Heptane was used as an alternative fuel as a sensitivity check for the wood.

For mechanical ventilation, the fire source (wood crib or heptane) was calculated to a theoretical size of approximately 30 kW, equivalent to 5 MW in large scale. 5 MW corresponds to 1 car burning [9] [8]. A fire of 5 MW, corresponding to one car burning, is considered a reasonable limit where manual firefighting operations can be carried out. Therefore, this study has used a 5 MW fire to investigate mechanical ventilation measures. This is also in line with the “Small fire” scenario (A2) in the LASH FIRE risk model [32]. The two fire sources are shown in Figure 31.

Figure 31: Smaller wood crib fire source (left) and smaller heptane fire source (right) for mechanical ventilation tests.

Free burning tests were conducted before the test scenarios with both fire sources.

For mechanical ventilation, the smaller wood crib fire source was built of wooden studs with dimension 28 *28 mm^2 and with a total length, width, and height of 0.35 * 0.25 * 0.17 m^3 consisting of three layers in transversal and three layers in longitudinal direction. The smaller heptane fire source was circular tray with diameter 0.225 m. The tray was filled with 2.33 litres of heptane for each test. For mechanical ventilation, the fire source was placed on two different locations in different scenarios. The fire source was for the majority of the performed tests placed in the middle of the model, but for some of the tests the fire source was placed in the joint between section 9 and 10, as shown in Figure 32 and Figure 33.

7.2.3.2.2 Instrumentation and documentation.

The instrumentation for the mechanical ventilation test series was largely the same as for the natural ventilation test series, as documented in 7.2.3.1.2. The following lists the differences between the test series in the instrumentation and documentation:

- There were no openings in the hulls during the mechanical ventilation tests.
- For the mechanical tests, a thermal camera was also filming inside the model.
- The CO, CO_2, O_2 sampling points were placed at 9.15 m and were located 0.15, 0.3 and 0.55 m from the inner roof.
- For some of the mechanical ventilation scenarios, when the fire was located between sections 9 and 10, the HRR was measured with the small hood calorimeter instead of the weighing platform (see further description in section 7.3.2).

Figure 32 and Figure 33 show the instrumentation for the mechanical ventilation tests.

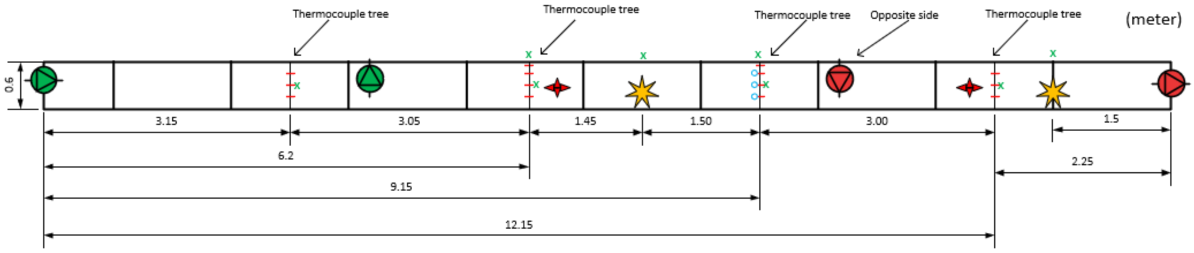


Figure 32: Side view of the model with instrumentation for mechanical ventilation tests. Section 1 is furthest to the left, and Section 10 is furthest to the right. The fire is either placed in Section 6 or between Section 9 and Section 10.

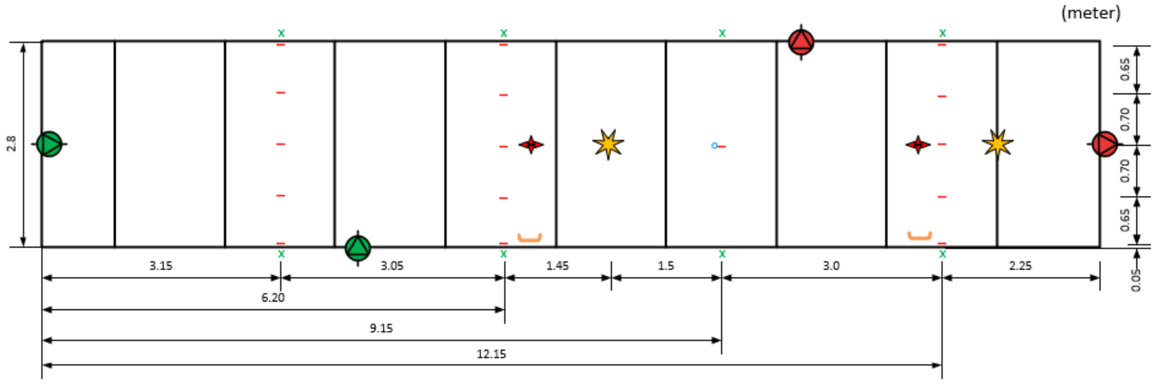


Figure 33: Top view of the model with instrumentation for mechanical ventilation tests. Section 1 is furthest to the left, and Section 10 is furthest to the right. The fire is either placed in Section 6 or between Section 9 and Section 10.

7.3 Obtention of the Heat Release Rate

Main author of the chapter: Stina Andersson, RISE.

During the tests, the heat release rate is measured by two different methods: a method based on the oxygen consumption measured by the extraction of gas to a hood calorimeter, and a method based on the measurement of the mass loss rate of the fuel measured by a weighing platform and multiplication by heat of combustion.

7.3.1 HRR measured with weighing platform

The obtention of the HRR with a weighing platform consists of monitoring and recording the mass loss rate of the fuel and multiplying this mass loss rate by the heat of combustion and the combustion efficiency, using the following equation:

$$HRR = \varepsilon \times \Delta H_C \times \dot{m}$$

Equation 11

With

ΔH_C: Heat of combustion [J/kg]

$\dot{m}$: Mass loss rate of fuel [kg/s]

ε: Efficiency of the combustion, $0 < \varepsilon < 1$

7.3.1.1 Weighing platform

To measure fuel mass loss rate and further calculate HRR, a weighing platform was constructed and located underneath the centre of the model in section 6. Four holes were drilled through the bottom of the model and four poles were inserted into the model, connecting the weighing platform to a steel frame on the inside. On the steel frame a non-combustible board was placed, and the fire source was then placed on the board. The weighing platform is shown from beneath the model in Figure 34 and from the inside in Figure 35.

Figure 34: Weighing platform from beneath the model.

Figure 35: Weighing platform from inside the model.

7.3.2 HRR measured with hood calorimeter

The measurement of heat release rate directly with the hood calorimeter is based on the oxygen consumption through the relation given by Huggett [33] stating that for each gram of oxygen depleted by the combustion, 13.1 kJ (+/- 5 %) of energy has been created.

7.3.3 Calculation of combustion efficiency

Combustion efficiency “ε” is the ratio between the effective heat of combustion, ΔH_{eff} and the complete heat of combustion, ΔH_c [34].

$$\varepsilon = \Delta H_{eff}/\Delta H_c$$

Equation 12

The following values for ΔH_c were used and taken from SFPE Handbook of Fire Protection Engineering, 5th edition [35]:

$\Delta H_{c,wood} =$ 19.6 MJ/kg

$\Delta H_{c,heptane} =$ 44.6 MJ/kg

In the free burning tests, the effective heat of combustion was calculated using the following equation:

$$\Delta H_{eff} = \frac{Q_{total}}{m}$$

Equation 13

Where:

Q_{total}: Total amount of energy [kJ]

m: start weight of the fuel [kg]

In the free burning tests, the HRR was measured using the hood. The total amount of energy released during the test, Q_{total}, is given by calculating the "area under the HRR curve". This was done in Excel using the following equation:

$$Q_{total} = \Sigma \frac{HRR_1 + HRR_2}{2} \times (t_2 - t_1)$$

Equation 14

Where:

HRR_1: HRR at time 1 [kW]

HRR_2: HRR at time 2 [kW]

t_1: time 1 [s]

t_1: time 2 [s]

Based on the previous equations, the following efficiency during free burning tests (in open atmosphere) have been found:

$$\varepsilon_{free\ burning,heptane,large\ pan} = 0.931$$

$$\varepsilon_{free\ burning,heptane,small\ pan} = 0.910$$

$$\varepsilon_{free\ burning,large\ woodcrib} = 0.623$$

$$\varepsilon_{free\ burning,small\ woodcrib} = 0.802$$

For the natural ventilation test series, the combustion efficiency was found by using the total amount of energy of the free burning test as a reference and compare what value of ε resulted in a similar value. Using this method, the combustion efficiency for tests where heptane was used was 0.79. For the two tests in the natural ventilation series where wood crib was used as a fuel, 1-3 and 1-5, the combustion efficiency was calculated to be 0.51 and 0.61 respectively. The combustion efficiency for the materials used as fuel in the test series are shown in Table 3.

For the mechanical ventilation test series, the combustion efficiency was calculated for the tests where the weighing platform was used to measure HRR. For the tests where the hood calorimeter was used to measure HRR, no combustion efficiency value was needed. For mechanical ventilation tests 2-2, 2-3 and 2-7, both the hood and the weighing platform were used. For those three tests, the combustion efficiency was determined by dividing the total amount of energy of the model test with the total amount of energy from the free burning test:

$$\varepsilon_{model\ test} = \frac{Q_{total,model\ test}}{Q_{total,free\ burning\ test}}$$

Equation 15

Where

$Q_{total,model\ test}$ was calculated according to Equation 14.

$Q_{total,free\ burning\ test}$ were the values noted above.

For the mechanical ventilation tests where only the weighing platform was used to measure HRR, either the calculated combustion efficiency for test 2-3 or 2-7 was used, depending on which of the two tests was deemed most similar. However, test 2-1 shows a higher CO/CO_2 ratio compared to both test 2-3 and test 2-7, indicating a lower combustion efficiency during test 2-1. To take this into account, the combustion efficiency for test 2-3 was used with a factor of 0.9. In addition to this, test 2-15 was performed with a large wood crib and a combustion efficiency for a smaller wood crib was therefore not deemed reasonable to use. Therefore, the combustion efficiency calculated for test 1-5 was used for test 2-15. The combustion efficiencies are listed in Table 11.

Table 11: Combustion efficiencies for tests.

Test series	Test scenario (fuel type)	Combustion efficiency, ε
Free burning tests	Large pan (heptane)	0.931
	Small pan (heptane)	0.910
	Large crib (wood)	0.623
	Small crib (wood)	0.802
Natural ventilation test series	1-1 (heptane)	0.79
	1-2 (heptane)	0.79
	1-3 (wood)	0.51
	1-4 (heptane)	0.79
	1-5 (wood)	0.61
	1-6 (heptane)	0.79
Mechanical ventilation test series	2-1 (wood)	0.618
	2-2 (heptane)	0.605
	2-3 (wood)	0.687
	2-4 (heptane)	N/A (measured by hood)
	2-5 (wood)	N/A (measured by hood)
	2-6 (wood)	N/A (measured by hood)
	2-7 (wood)	0.730
	2-8 (wood)	N/A (measured by hood)
	2-9 (wood)	N/A (measured by hood)
	2-13 (wood)	0.687
	2-14 (wood)	0.687
	2-15 (wood)	0.61

Water was applied at the bottom of the heptane trays to get an even fuel surface and to hinder buckling of the steel tray due to heat. It also makes it easier to regulate the temperature of the fuel and thereby reduce the risk of boiling of the fuel mass (heptane). Introducing water into the pan implied an uncertainty as some water was apparently evaporated during the testing. This was observed after investigation of the data from the weighing platform. To compensate for this, only data up until the time when the heptane fuel had been consumed was used. This time was obtained by comparing the testing notes and afterwards it was included in the calculations.

For the free burning tests, the fuel was not weighted before or after the test. It was therefore unknown how much fuel was consumed during the free burning tests, meaning that the start weight of the fuel "m" in Equation 13 was unknown. To address this, the start weight was calculated based on the volume of heptane and the density of heptane (weight = density × volume). The calculated ΔH_{eff} using Equation 13 inherently include some uncertainty for the free burning tests.

7.4 Test scenarios and procedure

Main author of the chapter: Stina Andersson, RISE.

Test scenarios for natural ventilation series and mechanical ventilation series are presented in the following sections.

7.4.1 Test scenarios – Natural ventilation

A total of 6 tests were conducted for natural ventilation. Tests with natural ventilation were carried out with variable configuration of the openings; even or compact (locally denser) distribution, and variable fire source; large heptane steel tray and large wood crib (400kW). Heptane was the main fire source used. The wood crib was used for sensitivity analysis to the main fire source heptane.

The openness of the long sides was calculated to 10% of the total area of the long sides for all the scenarios, i.e., comparative with the minimum openness for an open ro-ro space. The short end at section 1 was open in all test scenarios except for scenario 1-6 where the end was closed. Test 1-1 was a reference test with a standard opening configuration, i.e. four openings with 2.5 % of the total area. The openings and configurations are described in section 7.2.3.1. The natural ventilation scenarios are listed in Table 12.

Table 12: Natural ventilation scenarios.

Scenario number	Opening configuration	Fire source (nominal HRR)	Short end	Position of opening
1-1	Reference case (standard)	Heptane (400 kW)	Open	Middle – 2.5% x4 (125 mm from floor)
1-2	Evenly	Heptane (400 kW)	Open	Low – 1% x 10 (40 mm from floor)
1-3	Evenly	Wood crib (400 kW)	Open	Low – 1% x 10 (40 mm from floor)
1-4	Compact	Heptane (400 kW)	Open	Low – 1% x 10 (40 mm from floor)
1-5	Compact	Wood crib (400 kW)	Open	Low – 1% x 10 (40 mm from floor)
1-6	Compact	Heptane (400 kW)	Closed	Low – 1% x 10 (40 mm from floor)

7.4.2 Test scenarios – Mechanical ventilation

A total of 12 tests were conducted for mechanical ventilation. The fan settings were varied. The aim was to model both ordinary, reversed, and double capacity of the fan.

The fire source was mainly varied between the small wood crib and the small heptane bowl. Wood crib was the main fire source. The heptane was used for sensitivity analysis for the main fire source wood crib. For scenarios 2-13, 2-14 and 2-15 the short end was open. For scenario 2-15, the large wood crib was used instead of the small. The position of the fire source was either in the centre of the model in section 6 or in the joint between section 9 and 10.

The mechanical ventilation scenarios are listed in Table 13.

Table 13: Mechanical ventilation scenarios.

Scenario number	Fire position	Fire source (nominal HRR)	Fan settings	Short end
2-1	Section 6	Wood crib (30 kW)	10 ACPH, off at 3.5 min	Closed
2-2	Section 6	Heptane (30 kW)	10 ACPH, keep fans on	Closed
2-3	Section 6	Wood crib (30 kW)	10 ACPH, keep fans on	Closed
2-4	Section 9/10	Heptane (30 kW)	8 ACPH, keep fans on	Closed
2-5	Section 9/10	Wood crib (30 kW)	8 ACPH, keep fans on	Closed
2-6	Section 9/10	Wood crib (30 kW)	16 ACPH, keep fans on	Closed
2-7	Section 6	Wood crib (30 kW)	20 ACPH, keep fans on	Closed
2-8	Section 9/10	Wood crib (30 kW)	8 ACPH, start fans at 3.5 min.	Closed
2-9	Section 9/10	Wood crib (30 kW)	8 ACPH, start fans at 21 min.	Closed
2-13	Section 6	Wood crib (30 kW)	Fans off.	Open
2-14	Section 6	Wood crib (30 kW)	10 ACPH, keep fans on, only supply fans.	Open
2-15	Section 6	Wood crib (400kW)	Fans off.	Open

7.4.3 Test procedure

The test procedure was the same for all test series.

The measurements were started 2 minutes before ignition (-02:00) and the video cameras were started 1 minute before ignition (-1:00). For the mechanical ventilation scenarios where fans were used, the fans were started just before the measurements.

Ignition was carried out with a stick through the hatch in the model's side plating. Ignition took place at time 00:00. The hatch to the model was then closed.

Between the tests, the model was cooled down, the fire source was replaced, the opening or fan capacity was changed, and the instrumentation was checked and cleaned if necessary. An overall check of the model was also performed between the tests to check if any parts (i.e. gypsum) needed replacement.

For heptane fires, the fuel was consumed before the test ended. For wood cribs, the test was ended after 25 minutes.

8 Natural ventilation for ro-ro space ventilation

Main author of the chapter: Stina Andersson, RISE.

The number of fires in ro-ro spaces are significant and can result in very serious consequences for the ship and the crew onboard. Ventilation is crucial to the growth, intensity and burning time of fires in ro-ro spaces. In case of a fire, the permanent openings in an open ro-ro space will feed the fire with oxygen from the outside. Two examples of severe fires that started in open ro-ro spaces are the 2014 fire onboard M/S Norman Atlantic and the 2015 fire onboard M/S Sorrento [15]. Natural ventilation through side openings was pointed out as something that worsened the fire development in an accident report for the Sorrento fire, and the recommendations includes “Side openings of open cargo decks of ro-ro ships, to prevent/mitigate the devastating effects produced by the uncontrolled inflow of external air” [36].

8.1 Computer simulations

For natural ventilation the safety measures considered is to changed percentage and/or configuration of side openings in open ro-ro spaces. Based on that, the following question were identified for further studies regarding natural ventilation:

- Can the same air exchange rate as a closed ro-ro space with 10 ACPH be maintained if the side opening area is reduced below 10%?

8.1.1 Simulation results: natural ventilation in an open ro-ro space

Main author of the chapter: Stina Andersson and Robert Svensson, RISE

The air exchange without a fire have been studied for an open ro-ro space (deck 4 of Stena Flavia) with different opening percentages. The air that initially was contained within the ro-ro space at the beginning of the simulation has been tracked. The results were then compared to a closed ro-ro space with mechanical ventilation (deck 3 of Stena Flavia). The closed ro-ro space has a better air exchange rate than 10 ACPH, with half the original air extracted in 154 s. The ventilation of the closed ro-ro space has higher than 10 ACPH since the model is based on fan curves from the fans installed at Stena Flavia. As a reference an extraction of half the air volume in 180 s should be used, which is the theoretical value for 10 ACPH.

The air exchange time for the open ro-ro space is dependent on the wind conditions in the simulations. Therefore, simulations have been conducted with different wind conditions. Traveling speed also affects the air exchange time. When simulating scenarios without any wind, a traveling speed of 16 knots have been assumed. When simulating scenarios with wind (2.5 and 7.5 m/s), it is assumed that the ship is stationary (0 knots) and that the wind hits perpendicular to the long side of the boat. This is to consider the scenario that the ship is in port which is considered as a conservative scenario it could also be a scenario for a ship that has turned the ship to let the wind hit perpendicular to the side.

Below are result from the different wind scenarios presented. The results of the simulations are summarized in Figure 36, Table 14 and Figure 37.

No side winds

- With an opening area of 10%, and a traveling speed of 16 knots, the original air concentration is halved in 130 s (14 ACPH), which is faster than 10 ACPH (180 s).
- With an opening area of 4%, and a traveling speed of 16 knots, the original air concentration is halved in 266 s (6.8 ACPH). This is worse than the reference case.

7.5 m/s side wind (Baltic Sea average wind speed)

- With an opening area of 10%, the original air concentration is halved in 28 s (64 ACPH).
- With an opening area of 4%, the original air concentration is halved in 58 s (31 ACPH).

Both the above results in a better air exchange compared to the reference case.

2.5 m/s perpendicular side wind

- With an opening area of 10 %, the original air concentration is halved in 78 s (23 ACPH). This is better than the reference case.
- With an opening area of 4 %, the original air concentration is halved in 166 s (11 ACPH). This is better than the reference case.

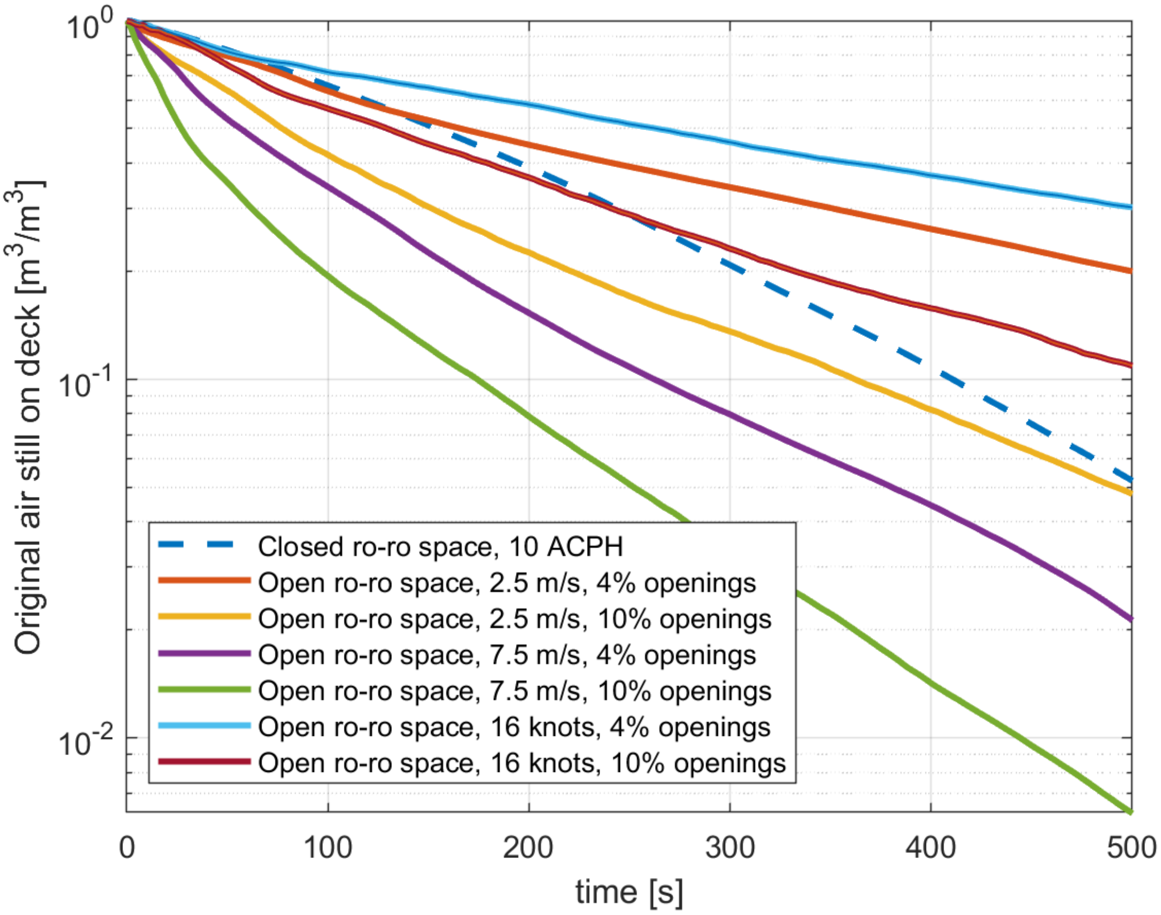


Figure 36: amount of the "original air" still contained within the ro-ro space over time. The amount is the average concentration for the whole ro-ro space with a ceiling.

Table 14: Time to reduce original air to 50 % with different ventilation scenarios.

Ro-ro space type	**Ventilation**	**Openings**	**Reduction of original air to 50 % [s]**
Closed (reference case)	10 ACPH, mechanical	None	154
Open	2.5 m/s, side wind	4 % side, aft open	166
Open	2.5 m/s, side wind	10 % side, aft open	78
Open	7.5 m/s, side wind	4 % side, aft open	58
Open	7.5 m/s, side wind	10 % side, aft open	28

Open	16 knots (8.23 m/s) from the front	4 % side, aft open	266
Open	16 knots (8.23 m/s) from the front	10 % side, aft open	130

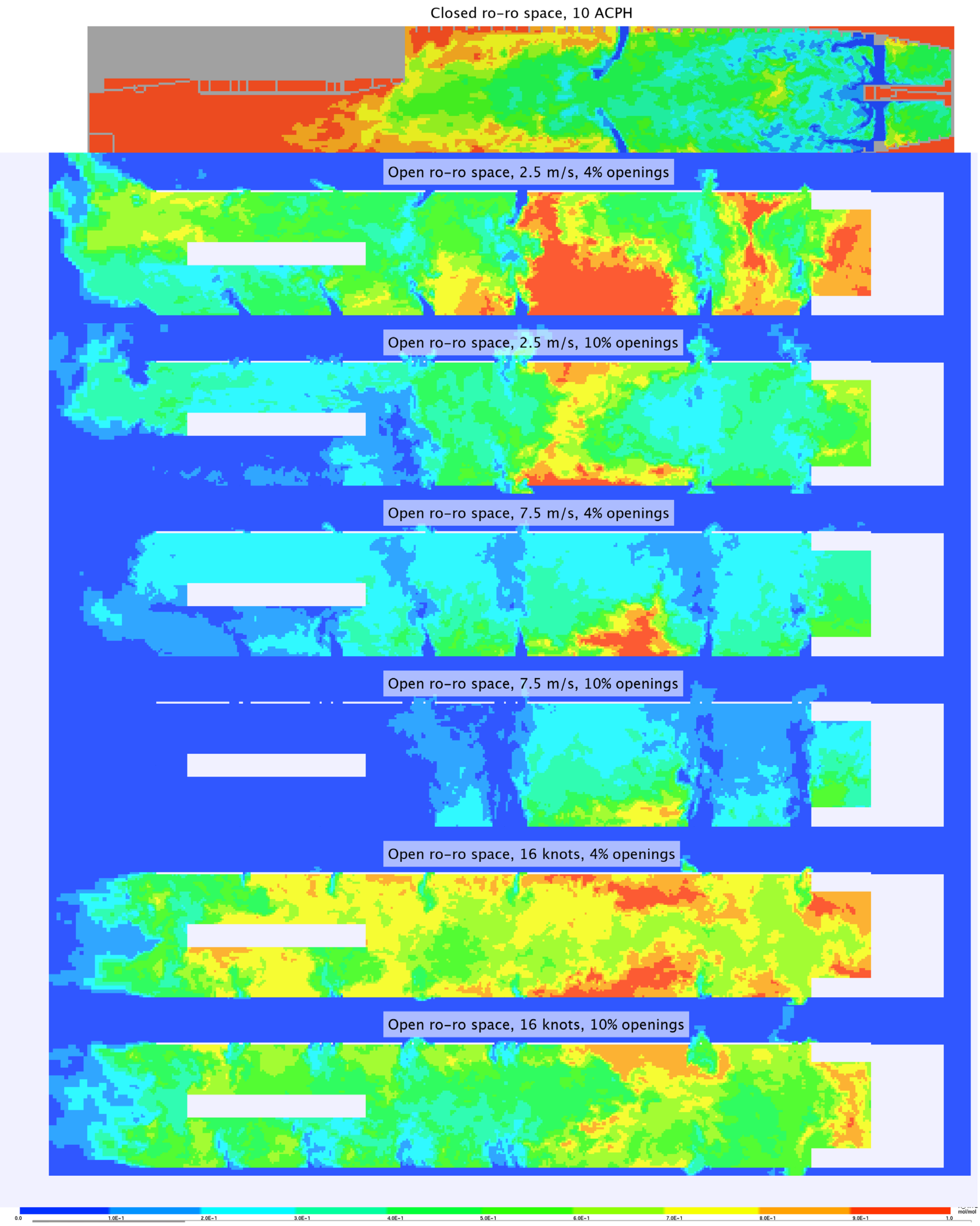


Figure 37: The amount of original air still in the ro-ro space after 2 min from a reference time. The slice is shown at the height in the middle of the between the deck and the ceiling.

8.1.2 Inputs taken from the simulations regarding natural ventilation

The output from the conducted simulations can answer the outlined question.

- *Can the same air exchange rate as a closed ro-ro space with 10 ACPH be maintained if the side opening area is reduced below 10%?*

The performed computer simulations were not able to show that the sides openings could be reduced below 10% and still maintain the same air exchange rate as 10 ACPH in a closed ro-ro space. Based on this, it is not deemed feasible to further look into decreasing the opening percentage in open ro-ro spaces without providing the space with mechanical ventilation.

It is still unclear whether 10 ACPH is a relevant capacity of the ventilation, and further studies of air quality in both closed and open ro-ro spaces can be done to investigate this. It is still unclear how the configuration of the permanent openings in an open ro-ro space affects the fire development.

8.1.3 Discussion on simulation result

The simulated scenarios with 10 % side openings and open aft show better or similar air exchange than the reference case with 10 ACPH on a closed ro-ro space. The open ro-ro space with 4 % side openings and open aft show a slower rate of air exchange than the closed ro-ro space when the side wind is low (2.5 m/s) or there is now side wind, and the boat is traveling in 16 knots.

The scenario with 10% side openings + aft open that was simulated without any side wind, travelling at the speed of 16 knots, is considered to represent the worst credible scenario. Even though no side wind is unlikely, the scenario is deemed credible when considering the effect of speed wind attributed by the travelling speed of 16 knots. A scenario where the travelling speed is 0 knots, and the side wind is 0 m/s might occur in port would result in worse air exchange results but is deemed a not credible scenario to consider.

The results for natural ventilation in this study is based on a reference case for air exchange rate, namely the air exchange rate when using 10 ACPH in a closed ro-ro space. This reference case is based on SOLAS II-2/20.3.1.1.1. If the reference case for air exchange rate had been different, it would likely have had an impact on the result and the conclusions. However, the reference case for air exchange rate is deemed reasonable to use since it is in line with the capacity of ventilation systems required by SOLAS.

8.2 Model scale tests

Tests with natural ventilation were focused on studying the effects on the HRR, gas temperatures, steel temperatures and gas concentrations with the different opening configurations. The HRR inside the model was determined by mass loss rate through the usage of the weighing platform.

Heptane was used as main fuel during the tests with natural ventilation. The main reason was to compare the results obtained in this study to the RO5 study, where heptane was used as fuel [1].

The aim was to create a fire which in large scale was equivalent to 70 MW. This corresponds to a fire of approximately 400 kW in the model scale tests (see scaling laws in 7.2.3.1.1). The achieved HRR in the tests was 300 to 600 kW and all the tests have a peak HRR above 1000 kW, which occurs just after 10 minutes.

The initial weight of the fuel is needed to calculate the HRR (through the use of effective heat of combustion, ΔH_{eff}, see Equation 13. The initial weight of heptane was calculated based on the volume of heptane in the pan and the density of heptane (density × volume = weight). Since the heptane was not weighted before the free burning test the calculated value of ΔH_{eff} for heptane during the free burning test has a level of uncertainty to it.

The total energy released has been calculated for all tests and the results are presented in Table 15.

Table 15: Total energy for tests with natural ventilation using heptane as a fuel and free burning test.

Scenario number	Total Energy (MJ)
Free burning heptane	766
1-1	764
1-2	733
1-4	760
1-6	745

The total amount of energy during the free burning test was 766 MJ. Analysis of the energy calculations show that all scenarios are reasonable, and the variation is low. All the calculated values of total energy are within 5% of the measured total energy of the free burning tests. All tests had 27 litres heptane as fuel initially and all the heptane fuel was expected to be consumed during the tests. Water was added to the heptane steel pan, and it became stratified due to density difference. The water has higher density and protects the steel pan from being damaged during the tests. Further reason is that water creates an even surface and better regulates the temperature of the fuel and thereby reduces the risk of boiling of the heptane. The boiling temperature for water and heptane is very similar, namely 100℃ and 98.4℃, respectively.

8.2.1 HRR Analysis

The aim of the test series for natural ventilation was to study HRR development when different opening configurations are used, and to compare the results to a reference case. Test 1-1 constituted the reference case.

Figure 38 shows HRR for the natural ventilation tests using heptane as a fuel (Test 1-1, Test 1-2, Test 1-4, and Test 1-6) as well as the HRR for the free burning test with heptane (made directly under a hood calorimeter).

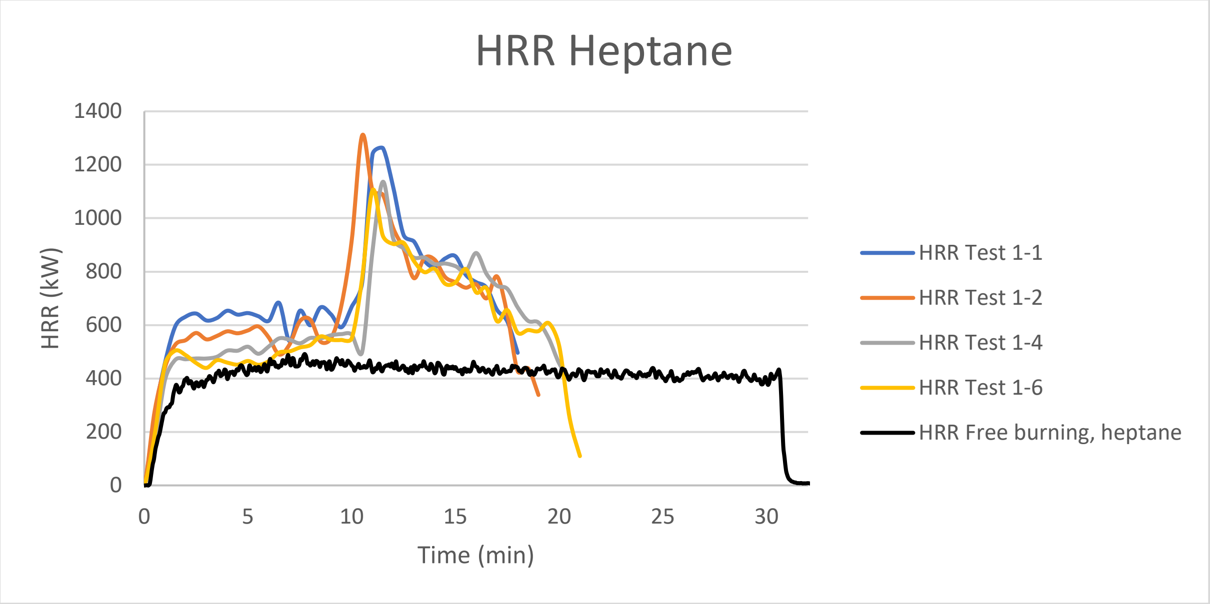


Figure 38: HRR comparison of heptane scenarios and free burning (about 400 – 470 kW).

The heptane tests 1–1, 1-2, 1-4 and 1-6 (tests inside the model) show clearly a different HRR development compared to the free burning test. The HRR varies from 400 kW to 470 kW with an average of around 430 kW in the free burning test. The tests inside the model have an overall higher HRR, around 400 to 600 kW initially. All four tests inside the model show an initial steep development reaching well above 400 kW, followed by a stabilisation between 1 and 10 minutes. During this time, the highest HRR value is seen for Test 1-1 and 1-2 that maintain a HRR value around 630 kW and 530 kW, respectively. The lowest HRR value during this time is seen for test 1-6 and 1-4 that maintain a HRR value around 450 kW and 500 kW, respectively.

It is known from previous studies [37] that the HRR of the same fuel will be higher in enclosed volume than in free burning test. This is due to re-radiation from the steel pan itself, from walls, and from ceiling to the fire source as well as re-radiation from the hot smoke layer.

Just after 10 minutes into the tests all four tests show a steep increase in HRR, with a short peak HRR between 1100 and 1300 kW before a drop in HRR followed by a slower decrease of HRR until the fire extinguish when all the fuel is consumed. The steep increase can be explained by boil over in the heptane steel pan, mainly due to the heptane but probably also because of the water underneath the heptane (both have very similar boiling point, 100℃ and 98.4℃, respectively). The consequence of this phenomenon is higher HRR. The main reason is that after the boil over, the exposed fuel area of the heptane is increased considerably due to very high boiling activities of the entire heptane volume (like a boiling water in a stew). Due to excess of unburned liquid and vapours over a distance further away from the heptane surface the mass loss burning rate is drastically increased and consequently, a large flame volume in vicinity of the fire is created. This can be observed visually in videos from the tests, see Figure 39. The direct consequence of a boil over of the heptane is an increase in HRR.

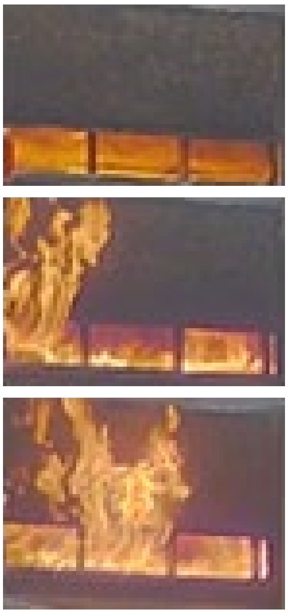


Figure 39: Snapshot of video from test 1-2. Photo shows the fire 5, 10, and 15 minutes after ignition.

8.2.1.1 Comparison of HRR

The heat release rate of the tests 1-1 and 1-2 are similar. Both test 1-1 and 1-2 have a peak HRR around 1300 kW. Test 1-1 has four openings in the middle of the side plating's (walls) and the short end in Section 1 is open. Openings placed in the middle of the side plating is more comparable to how the openings are configurated on real ro-ro ships compared to the lower placed openings in the other test scenarios. The size of one opening is larger in this test compared to the other tests, and the high HRR can possibly be explained by other conditions for in and out flow of fresh air. Test 1-2 has an even distribution of 10 low openings and one end open.

The heat release rate of the tests 1-4 and 1-6 are similar. Both test 1-4 and test 1-6 have a peak HRR around 1100 kW. Both these scenarios have compact distribution of low openings, with the difference that test 1-6 has short ends closed while test 1-4 has one short end open. The tests with a compact opening distribution (test 1-4 and 1-6) show lower HRR values and longer burning times compared to even opening distribution (test 1-2) and the reference case (test 1-1). This indicates that compact openings give a less severe fire development. It should be noted that the tests have only been made with fire at the centreline. A different position of the fire, e.g. closer to an opening, could also have an effect on the HRR results.

8.2.2 Temperatures

Temperatures inside the model and temperatures of the steel on the outside of the model are further presented here.

Figure 40 presents a comparison between the gas temperature measured by the vertical thermocouple element in section 3 and section 5 for the natural ventilation test using heptane as a fuel. The graph shows the measurement point located at 0.15 m from the roof of the model.

The gap in the data for test 1-4 seen in Figure 40 to Figure 43 is due to a network error that occurred around 20.5 min after ignition. The error occurred just before the fire extinguished in test 1-4.

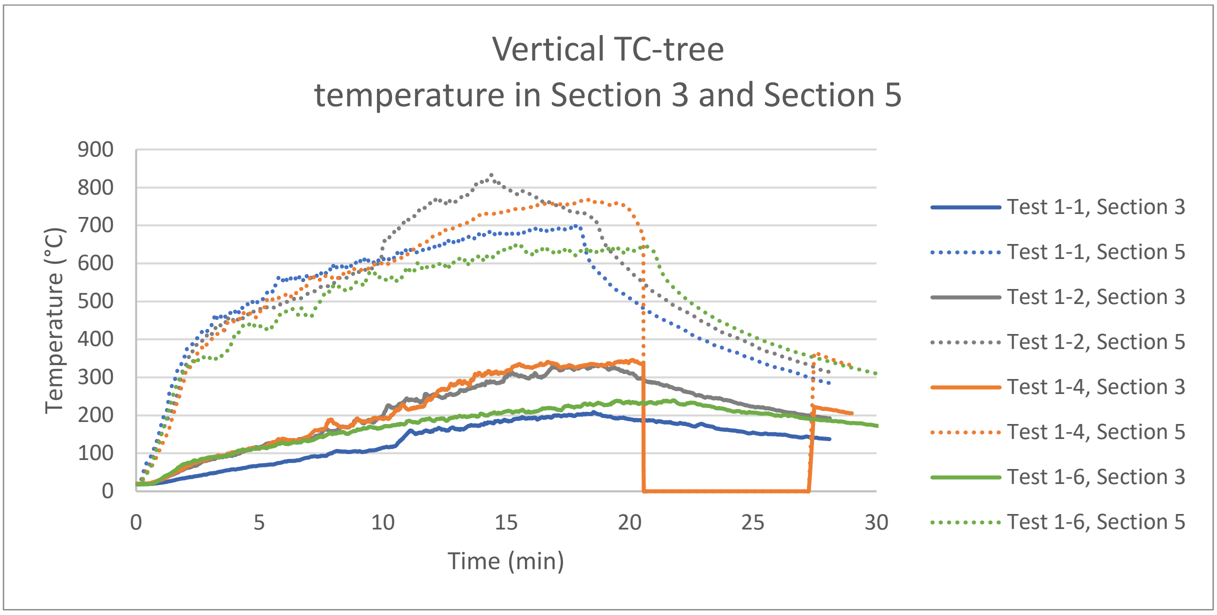


Figure 40: Comparison of gas temperature (vertical) in section 3 and in section 5. Measured at 0.15 m from the ceiling of the model. Fuel: heptane.

Figure 41 present a comparison between the gas temperature measured by the horizontal thermocouple element in section 3 and in section 5 for the natural ventilation test using heptane as a fuel. The graph shows the measurement point located at 0.7 m from the side of the model.

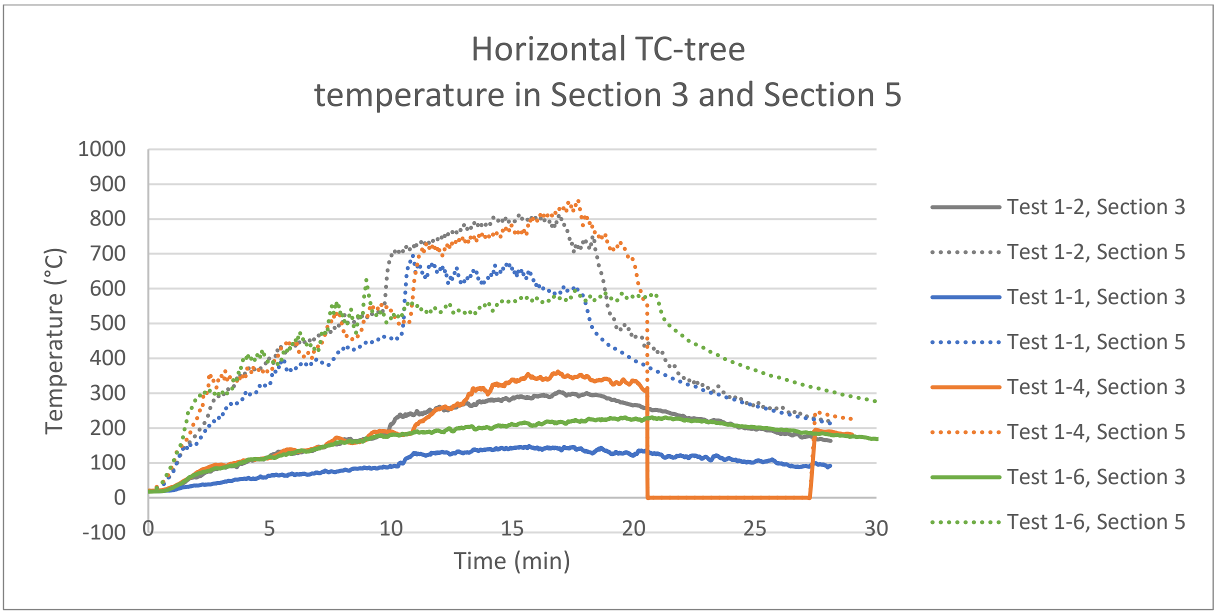


Figure 41: Comparison of gas temperature (horizontal) in section 3 and in section 5. Measured at 0.15 m from the ceiling of the model. Fuel: heptane.

Figure 42 presents a comparison between the gas temperature measured by the vertical thermocouple element in Section 7 and Section 9 for the natural ventilation test using heptane as a fuel. The graph shows the measurement point located at 0.15 m from the ceiling of the model.

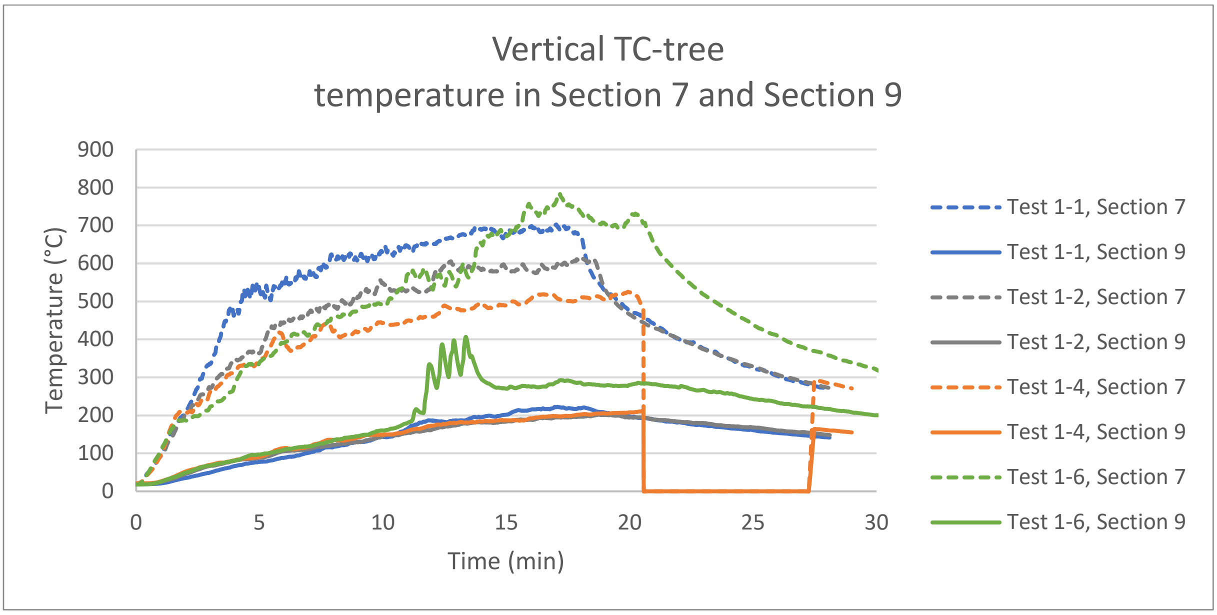


Figure 42: Comparison of gas temperature (vertical) in section 7 and section 9. Measured at 0.15 m from the ceiling of the model. Fuel: heptane.

Figure 43 presents a comparison between the gas temperature measured by the horizontal thermocouple element in section 9 for the natural ventilation test using heptane as a fuel. The graph shows the measurement point located at 0.7 m from the side of the model.

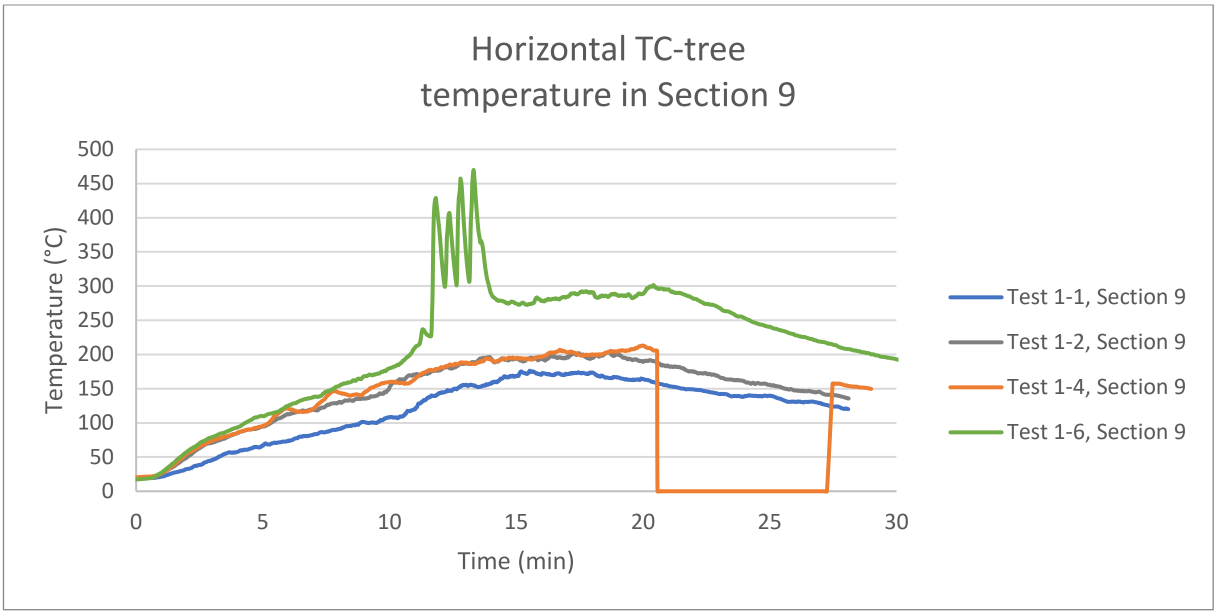


Figure 43: Comparison of gas temperature (horizontal) in section 9. Measured at 0.7 m from the side of the model. Fuel: heptane.

The gas temperatures vary between sections. The highest gas temperatures are as expected in the sections closest to the fire (section 5 and section 7). Sections further away from the fires have lower gas temperatures (section 3 and section 9). The reason is mainly the distance between the fire source and the measurement element as the gas temperature drops rapidly radially due to heat losses, mixing of gases and exhaust through ventilation openings. The high temperatures in section 5 and section 7 (mostly well over 550℃) indicate large volume of flames along the ceiling. The lower gas temperatures in sections 3 and section 9 (mostly around 300℃) indicate that there is only smoke at this location.

Comparing Figure 42 and Figure 43, the gas temperatures are about the same for the horizontal and the vertical measurement points in section 9. The gas temperatures are higher in Section 7 compared to Section 9, which is natural since the fire is in Section 6.

For test 1-6, the temperature in section 9 is higher compared to the other tests, indicating a descending of the hot smoke layer in section 9. This might be explained by the fact that the short end in test 1-6 is closed, keeping the hot smoke inside.

An oscillation can be seen between 12 and 15 minutes for test 1-6 both in the vertical and horizontal temperatures. Video material from the test show that flames are visible from the openings in section 9 during this time.

For test 1-2, with even distribution, it can be observed that there is a tendency for about 100°C higher gas temperatures at section 3 and section 5, left of the fire (upstream), compared to the right side of the fire (downstream) in section 7 and section 9. Actually, the gas temperatures are nearly the same on both sides for test 1-1.

Figure 44 presents a comparison between the steel temperature measured above the fire in Section 6 for the natural ventilation tests using heptane as a fuel.

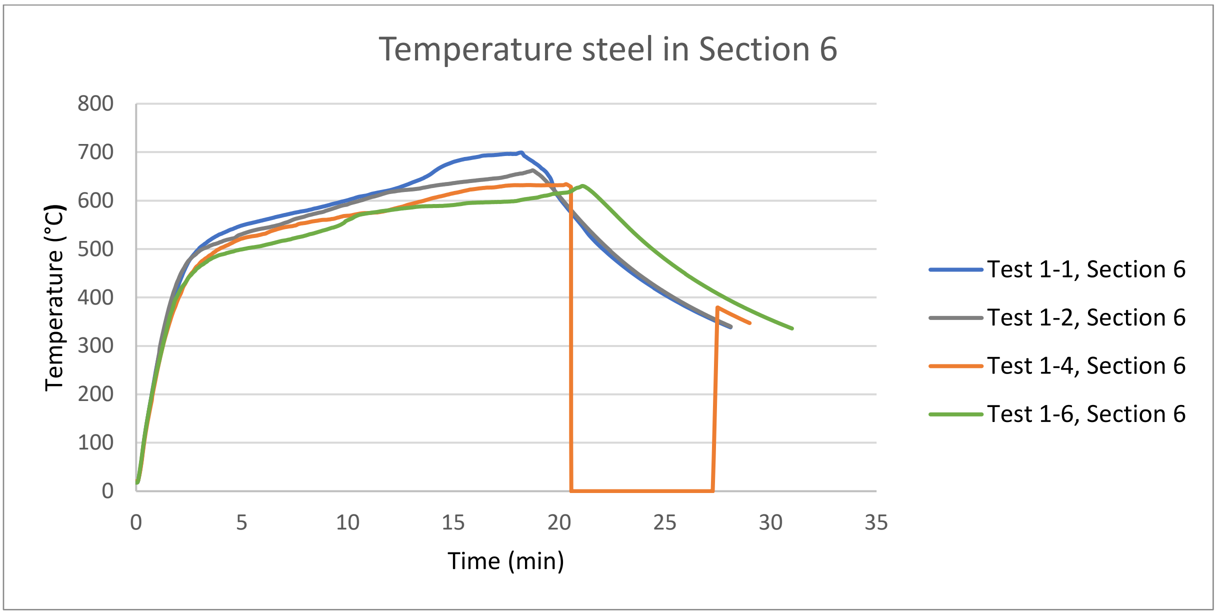


Figure 44: Comparison of steel temperature in Section 6. Fuel: heptane. The sudden drop to zero in Test 1-4 after 21 minutes and return to normal value after about 27 minutes is related to an instrument error.

The steel temperature in section 6 measured above the fire show that test 1-1 reached the highest steel temperature (around 700 °C), and test 1-6 reached the lowest steel temperature (around 615°C), see Figure 44. Test 1-6 have a closed end which is not the case in the other tests. The influence on the steel temperatures due to the short end closed is lower than expected as closing the end was expected to influence the results more which can be explained by the fact that the HRR in Test 1-6 was slightly lower than in the other tests of this series. The measured steel temperatures lie well in line with the HRR measured (see Figure 38).

Both inside gas temperatures and outside steel temperatures all indicate that close to the fire source (section 7) there is a strong stratification with flames and smoke, while further away (in section 9) there is low stratification of smoke and no presence of flames.

8.2.3 Gas analysis

O_2, CO_2 and CO have been measured at three heights in section 3. The highest measurement point was located 0.15 m from the inner roof of the model, whereas the lowermost measurement point was located 0.15 m from the floor of the model (see details in 7.2.3.1.2). The heptane steel pan had a height of around 0.13 m. The results for the highest located measurement points (0.15 m from the inner roof of the model) are compared in Figure 45, Figure 46 and Figure 47. Due to technical issues, there is no data from test 1-2.

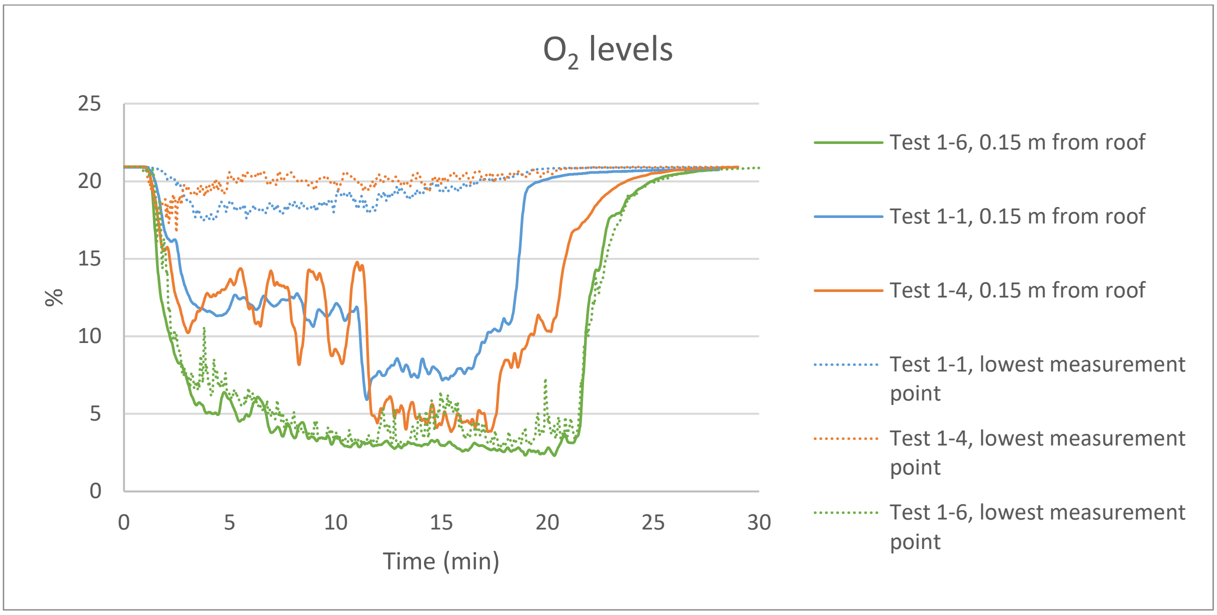


Figure 45: Comparison of O_2 levels. Measured in Section 3, 0.15 m (solid line) and 0.45 m (dashed line) from the inner roof of the model. Fuel: heptane.

In Figure 45, results from the lowest measurement point (0.45 m from the inner roof) have been included. This is to show that during test 1-6 where both short ends were closed, the O_2 levels drops even at the lowest measurement, indicating that the smoke layer height reached down to the lowest placed measurement point.

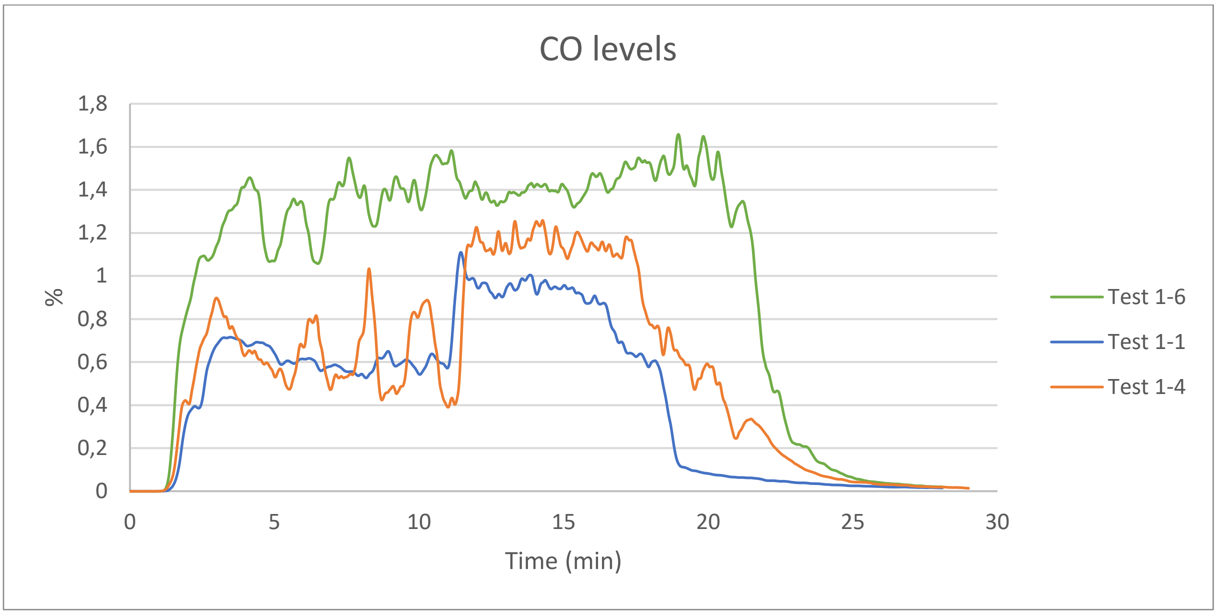


Figure 46: Comparison of CO levels. Measured in Section 3, 0.15 m from the inner roof of the model. Fuel: heptane.

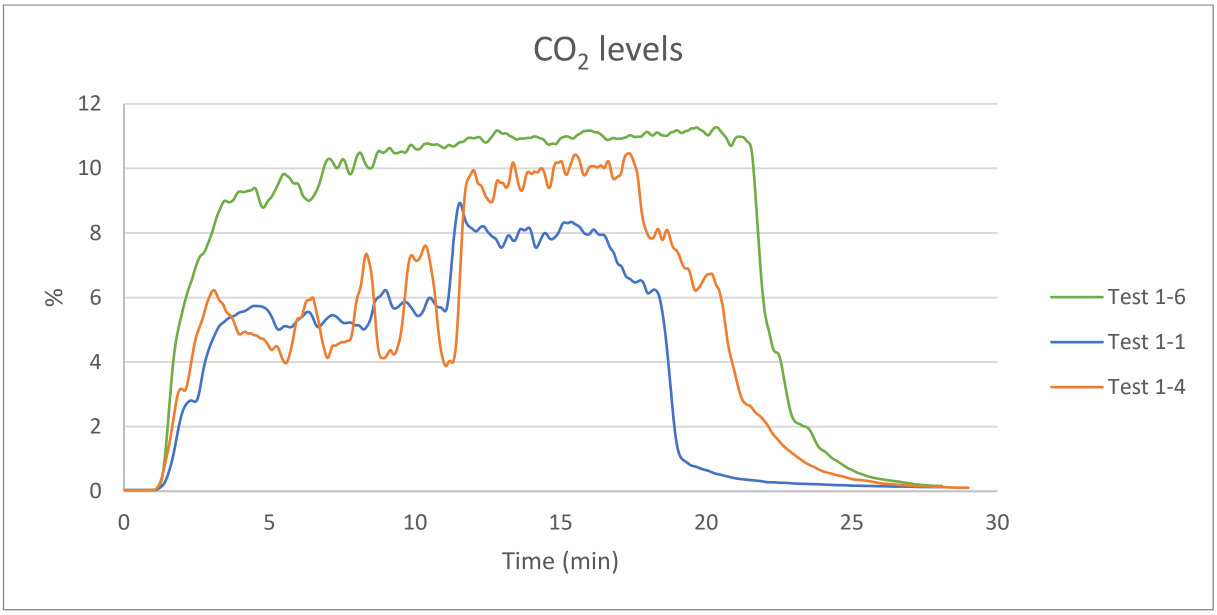


Figure 47: Comparison of CO_2 levels. Measured in Section 3, 0.15 m from the inner roof of the model. Fuel: heptane.

The O_2 level decreases while the CO_2 and CO levels increase. This is in line with the HRR increase after 10 minutes as shown earlier in Figure 38. The O_2 drops to 6% or lower for all tests at the highest placed measurement point. No fire was self-extinguished due to gas concentrations. In all tests the heptane fuel was completely consumed.

8.2.4 Inputs taken from the model scale tests regarding natural ventilation

The test results do not show any clear influence of the opening distribution. Even distribution of openings follows the same fire development as compact distribution of openings.

The tests with a compact opening distribution (test 1-4) show slightly lower HRR values and slightly longer burning times compared to even opening distribution (test 1-2) and the reference case (test 1-1). These differences are small, and it is not convincing that the compact or even distribution is having an effect of the fire development and the heat release rate compared to a standard opening configuration onboard ro-ro ship today (Test 1-1). A slight difference should, however, be mentioned regarding the scenario with closed short ends (test 1-6). This results in lower HRR almost the entire test time, compared to the other tests. The closed short end allows the smoke to accumulate and creates a slightly more severe environment with regards to temperature and smoke layer height.

8.3 Ship integration and cost assessment

Main author of the chapter: Obrad Kuzmanovic, FLOW

It is obvious that openings and ventilation configuration can play an important role on fire and smoke spreading. This chapter gives a review of natural ventilation from operational, design and construction aspects as well as cost assessment.

8.3.1 Operational, design and construction aspects

The lack of unambiguous procedure how to calculate side openings was often a problem in design practice. Therefore, the proposed guidance that the side should only consider the area of the long sides of ro-ro space is a good attempt in way of rules and design consolidation. Such consideration may however also lead to a reduced design flexibility where some arrangements will not fall into any ro-ro space definition. Specifically, the proposed definition where the side height of maximum 150 cm shall be allowed for the ship's long sides for a weather deck to still be considered exposed.

An example of a commonly used arrangement is a ro-ro deck exposed to the weather from above but with closed both sides (engine casing, etc.) and closed forward and/or aft (other ro-ro space, ramp).

As for openings configuration, the configuration regarding the fire issues could considerably influence the general and structural arrangement. Reducing the height of the openings would require a larger number of openings along the ship, where in some cases the requirement of 10% might not be possible to obtain due to other requirements such as closures in way of LSA, engine casings, communication and ventilation ducts or other arrangements. This would lead to banning of open ro-ro space and considerable influence on the ship design and operation as well as increased cost.

The results proved that the minimum openings area must be indeed 10% of the total area of open ro-ro space sides in order that required air changes per hour are obtained. Regarding the background of open ro-ro space, the definition regarding 10% of the total area of the space sides, whether it is derived from mathematical formula or from empirical evidence, is not clear and further understanding and evaluation of this can help to fulfil “adequate ventilation” as required in SOLAS II-2/20.1.3.

8.3.2 Cost assessment

No throughout cost assessment was made for natural ventilation aspects discussed and evaluated in this work. Brief comments on the costs were the following:

- Regarding definition of side openings this can be assumed to not lead to any additional cost compared to the current state.
- Regarding configuration of openings the following cost items are proposed to be considered:
    - Investment cost: design and drawings for specific open ro-ro space arrangements, additional equipment cost in case opening requirement for open ro-ro spaces cannot be fulfilled.
    - Operational cost: Reduced flexibility in cargo type in case opening requirement for open ro-ro spaces cannot be fulfilled, and increased fuel consumption due to additional required power for ventilation system, in case opening requirement for ro-ro space cannot be fulfilled.

8.4 Summary regarding natural ventilation

For natural ventilation, the performed computer simulations were not able to show that the sides openings could be reduced below 10% and still maintain the same air exchange rate as 10 ACPH in a closed ro-ro space. This indicates that, if the opening percentage is to be reduced, mechanical ventilation would be needed to achieve the required air exchange rate. Therefore, a reduced opening percentage in open ro-ro spaces is not deemed to be a feasible way forward without further investigations on air quality. Reduced opening percentage was not further studied in LASH FIRE.

In conclusion, the results indicate that mechanical ventilation would be needed to achieve the reference air exchange rate (SOLAS II-2/3.1.1) if the side openings percentage in an open ro-ro space was reduced to 4%. However, it is still unclear how the configuration of the side openings affects the fire development in an open ro-ro space. Since under ventilated scenarios are not suitable for computer simulations in FDS it will be needed to study how permanent opening configurations influence the fire development in test set up instead.

The natural ventilation tests were focused on fire development in open ro-ro space, using large fire scenario. For heptane, the tests with a compact opening distribution (test 1-4 and test 1-6) show lower HRR values and longer burning times compared to even opening distribution (test 1-2) and the reference case (test 1-1). Although the results indicate that compact openings result in a less severe fire development, the reduction in HRR is not significant to conclude that there is a benefit of having compact openings. This is supported by the sensitivity analysis using wood as a fuel in the test, which did not show a difference between a compact opening distribution and even opening distribution.

This study showed that closing the side openings results in a less intense fire (lower HRR). It also showed that keeping one short end open is enough to provide the investigated fire with enough oxygen to not become ventilation controlled, even if all side openings are closed. This result is supported by previous study, RO5 [1], where it also was concluded that having one short end open is enough to provide enough oxygen to sustain a fire in the ro-ro space.

When analysing the gas and steel temperatures there is no obvious trend in the results which can indicate what configuration is preferred. The built-up model shows signs of being better ventilated with the openings evenly distributed and thus creating a larger and more intense fire development.

In conclusion, there is no clear effect on the fire development when changing the opening configuration to low placed openings. Lowering the openings while keeping the opening percentage (10%) will not reduce the fire development inside an open ro-ro space. Changed configuration of side openings in open ro-ro spaces is not proposed for further assessment within the LASH FIRE project.

9 Mechanical ventilation for ro-ro space ventilation

Main author of the chapter: Stina Andersson and Anna Olofsson, RISE

9.1 Computer simulations

For mechanical ventilation the safety measures considered is the usage of reversible fans for closed ro-ro spaces (to facilitate manual interventions). The following questions were identified for mechanical ventilation in closed ro-ro spaces:

1. When should mechanical ventilation be considered in case of fire in a ro-ro space?
2. Will reversible fans help the crew to do a manual intervention?

9.1.1 Simulation results: Mechanical ventilation in a closed ro-ro space

Main author of the chapter: Stina Andersson and Robert Svensson, RISE

The environment close to the fire source has been investigated in the different fire scenarios. The three parameters visibility, incident radiative heat flux, and temperature have been investigated and compared to the critical values for all scenarios. In addition to this, smoke layer height has also been studied.

The results in this chapter have been investigated at a height of 1.9 m above deck, which means the volume elements extending 1.8 – 2.0 m above deck (in the CFD model). The results are also presented at 2.9 m above the deck and at a vertical plane along the deck through the fire source.

The results show that, with the fires of the size of one fully developed car fire of 5 MW, the limiting parameter is always visibility.

9.1.1.1 Visibility

The lack of visibility due to the smoke from the fire is the limiting parameter compared to the other studied parameters, in all simulated fire scenarios in the closed ro-ro space. This means that visibility reaches the critical value first.

The visibility, S, relates to the extinction coefficient, K (m^{-1}), according to [14]:

$$S = C/K \tag{3}$$

Where C is a non-dimensional constant depending on which object is observed through the smoke. For a light emitting evacuation sign $C = 8$ and $C = 3$ for a light reflecting sign. An extinction coefficient $K < 0.3$ or < 0.8 m^{-1} is needed to see a light reflective and light emitting sign, respectively, from 10 m away. In this study, the value for a light reflecting sign is used, i.e., $K < 0.3$ m^{-1}. I.e. 10 m visibility corresponds to an extinction coefficient $K < 0.3$ m^{-1}.

Values for visibility at pre-defined points, 5 and 10 m from the fire source both upstream and downstream, can be seen in Table 16.

Table 16: Simulation results for visibility at predefined reference points at 5 and 10 m from the fire source.

Scenario	**Ventilation**	**Fire position**	**Visibility 5 m from the fire (towards aft, towards front)**	**Visibility 10 m from the fire (towards aft, towards front)**
1	Off	fore	11 m, 48 m (5 min) 2.0 m, 2.6 m (10 min)	9.5 m, 37 m (5 min) 1.8 m, 3.2 m (10 min)
2	10 ACPH	fore	9.2 m, 3.5 m	10.6 m, 6.3 m

3	8 ACPH reversed	fore	8.0 m, 11.0 m	9.5 m, 13 m
4	16 ACPH reversed	fore	4.8 m, 16 m	3.9 m, 25 m
5	Off	centreline	20 m, 8.0 m (5 min) 1.6 m, 1.4 m (10 min)	29 m, 3.7 m (5 min) 1.6 m, 1.1 m (10 min)
6	10 ACPH	centreline	11 m, 5.6 m	10 m, 5.3 m
7	8 ACPH reversed	centreline	3.4 m, 6.2 m	3.2 m, 6.8 m

General results for scenario 1 to 4, based mainly on 2D-slice data, are described below:

- Scenario 1: Without ventilation the visibility is below 10 m for most of the deck area at 1.9 m height after 5 min and then decreases rapidly. This is the worst result for the visibility parameter of scenario 1 to 4.
- Scenario 2: For normal operation of the fans with 10 ACPH, the smoke is pulled through the whole ro-ro space by the fans. The visibility at height 1.9 m is at best 10 m.
- Scenario 3: For reverse operation of the fans with 8 ACPH the aft of the ship is free from smoke. The closest 80 m to the fire source is however similar to Scenario 2 at 1.9 m, where the visibility is mostly around 10 m.
- Scenario 4: For reverse operation of the fans with 16 ACPH, the situation at 1.9 m is considerably better than for scenario 1, 2 and 3. The simulations indicates that a visibility of 10 m can be achieved at a distance of 10 m from the fire source. This is the best result for the visibility parameter of scenario 1 to 4. Within 10 m from the fire source, the visibility decreases below 10 m. There is still a smoke layer that starts at approximately 3 m above deck which extends around 50 m away from the fire source, see Figure 50.

The visibility (light extinction coefficient, K) for the mechanical ventilation scenarios 1 to 4 where a 5 MW fire is burning on the starboard side in the front of the ship, is presented in Figure 48 to Figure 50. Within the red coloured areas in the figures, the visibility is less than 4.2 m (K = 0.72). The critical visibility distance of 10 m is light green (K = 0.3).

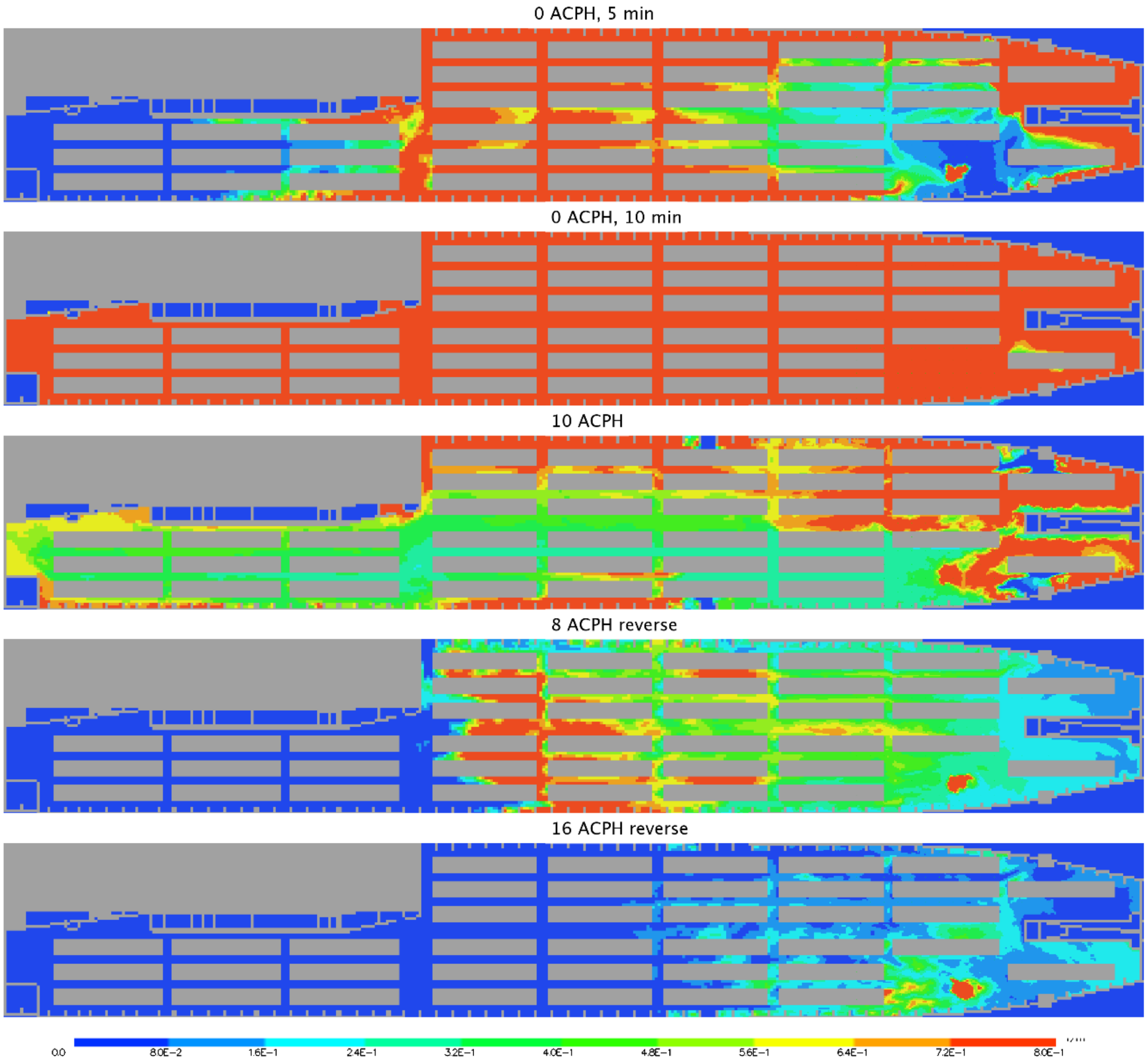


Figure 48: Light extinction coefficient [1/m] 1.9 m above the deck for all cases with the fire placed in the front.

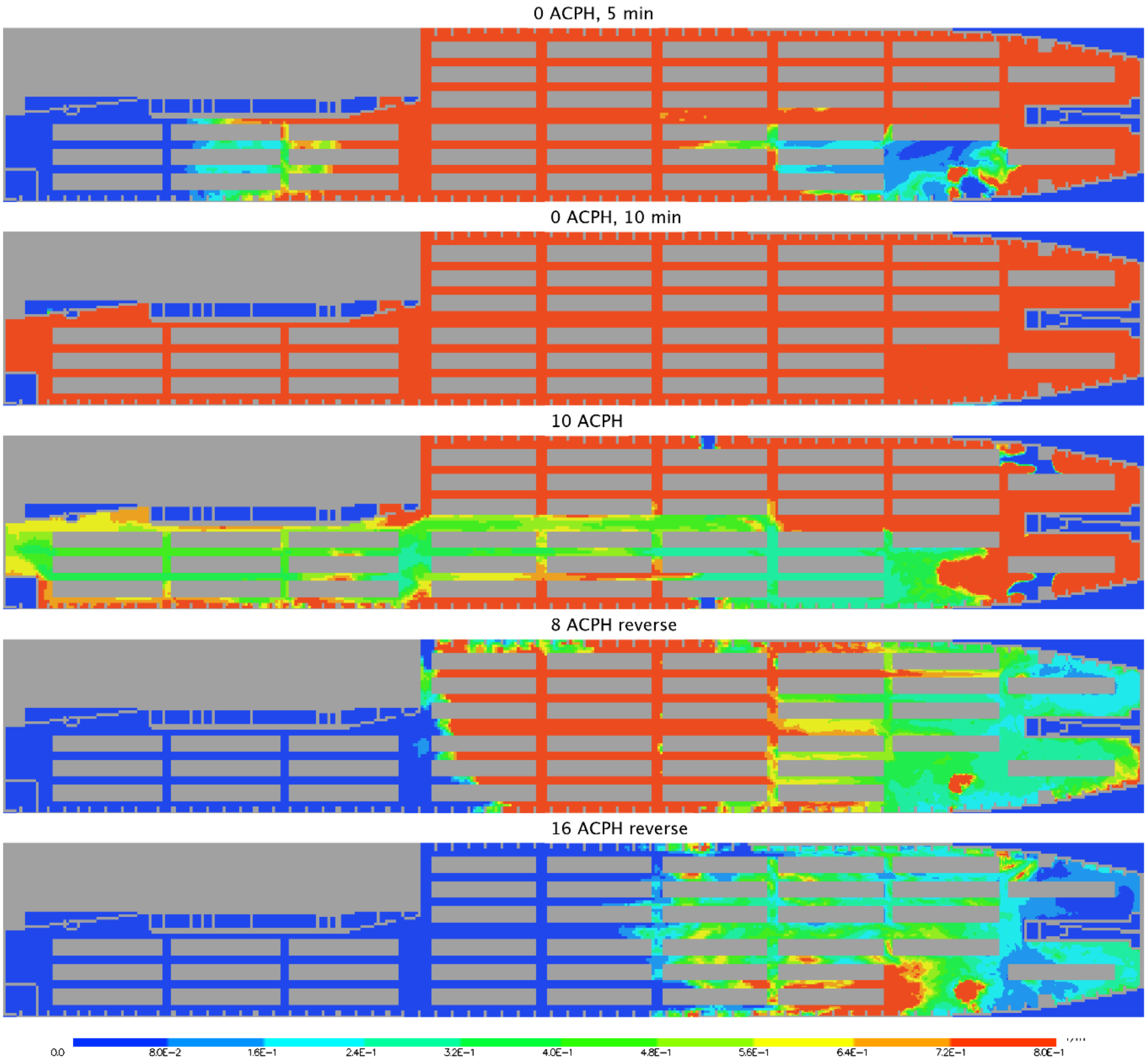


Figure 49: Light extinction coefficient [1/m] 2.9 m above the deck for all cases with the fire placed in the front.

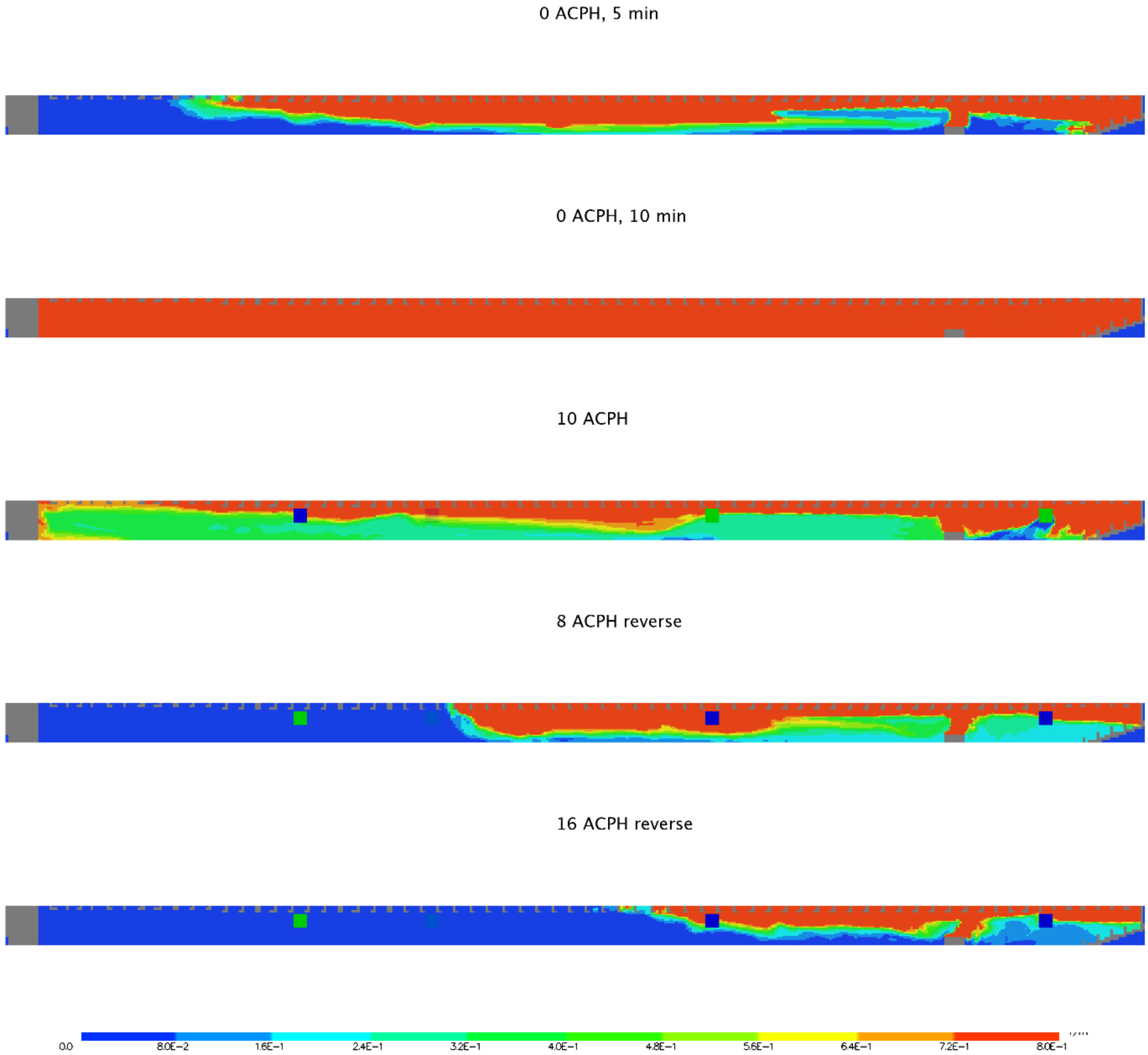


Figure 50: Light extinction coefficient [1/m] in a vertical plane through the fire source for all cases with the fire placed in the front.

General results for scenario 5 to 7 are described below:

- Scenario 5: Without any ventilation the situation is similar to scenario 1, when the fire is placed in the front without any ventilation. The visibility due to smoke after 5 min is below 10 m for almost the whole ro-ro space. This is the worst result for scenario 5 to 7.
- Scenario 6 & Scenario 7: The visibility for scenario 6 and 7 is similar for the 50 m closest to the fire source. The smoke is thinner downstream than upstream of the fire in both cases. The visibility downstream of the fire source is approximately 5-10 m for a reflective sign for both scenario 6 and 7. This is the best result for the visibility parameter of scenario 5 to 7.

In mechanical ventilation scenario 5 to 7, a 5 MW fire have been placed along the centreline around 2/3 of the ship length to the front. The visibility (light extinction coefficient, K) is presented in Figure 51 to Figure 53. Within the red coloured areas in the figures, the visibility is less than 4.2 m (K = 0.72). The critical visibility distance of 10 m is light green (K = 0.3).

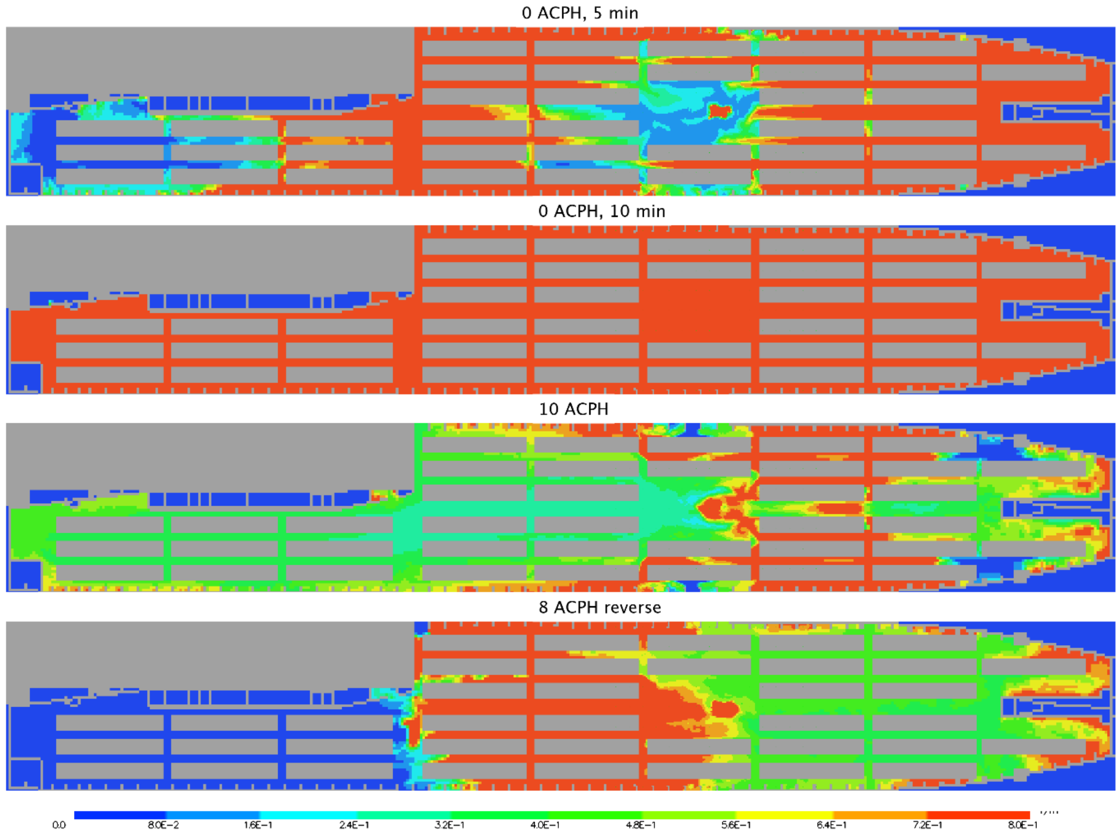


Figure 51: Light extinction coefficient [1/m] 1.9 m above the deck for all cases with the fire placed in the middle.

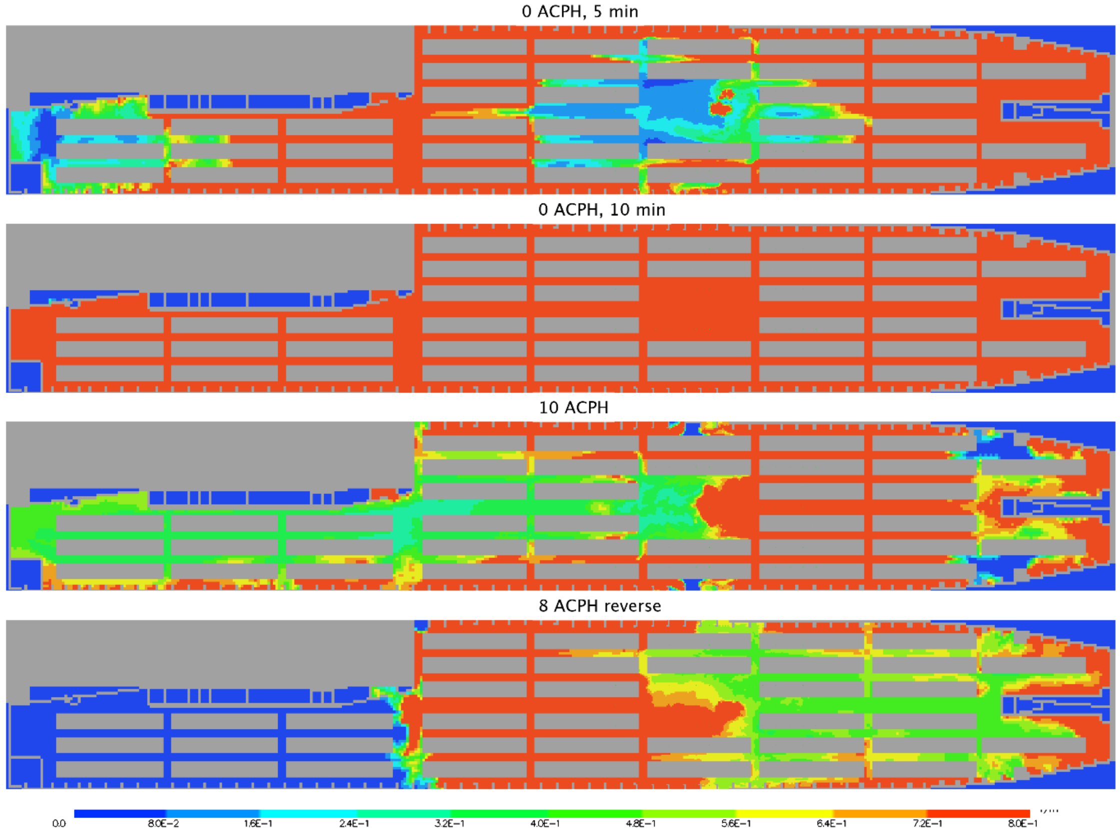
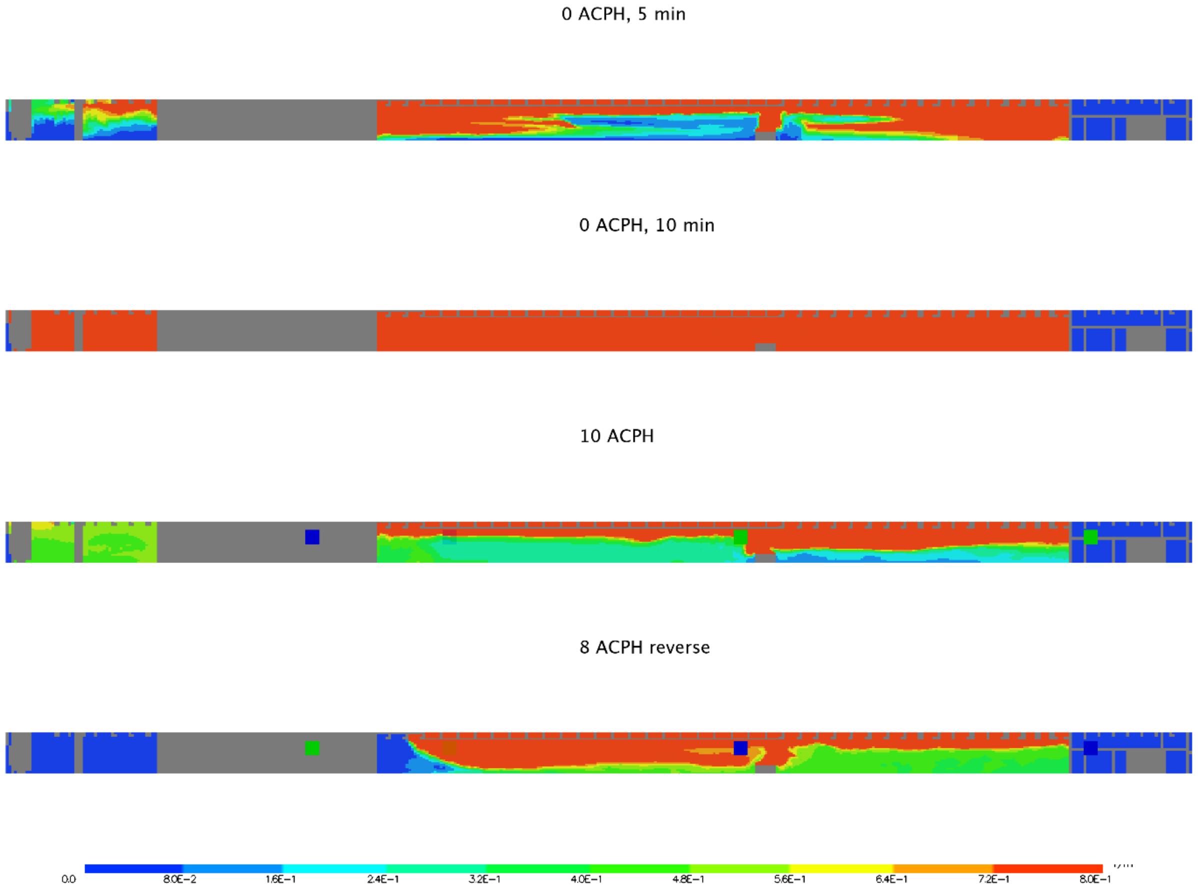


Figure 52: Light extinction coefficient [1/m] 2.9 m above the deck for all cases with the fire placed in the middle.



0 ACPH, 5 min

0 ACPH, 10 min

10 ACPH

8 ACPH reverse

Figure 53: Light extinction coefficient [1/m] in a vertical plane through the fire source for all cases with the fire placed in the middle.

9.1.1.2 Temperature

The temperatures in the air have been a less restricting parameter than the visibility. Temperatures were observed at 1.9 m and 2.9 m height above deck. The simulation results for temperature at 1.9 m above the floor at pre-defined positions, 5 and 10 m from the fire upstream and downstream, are presented in Table 17.

Table 17: Simulation results for temperature at predefined reference points at 5 and 10 m from the fire source.

Scenario	**Ventilation**	**Fire position**	**Temperature 5 m from the fire (towards aft, towards forward)**	**Temperature 10 m from the fire (towards aft, towards forward)**
1	Off	fore	42°C, 45°C (5 min) 53°C, 57°C (10 min)	47°C, 41°C (5 min) 60°C, 55°C (10 min)
2	10 ACPH	fore	52°C, 55°C	48°C, 38°C
3	8 ACPH	fore	37°C, 34°C	43°C, 34°C
4	16 ACPH	fore	35°C, 38°C	43°C, 32°C
5	Off	centreline	44°C, 43°C (5 min) 57°C, 57°C (10 min)	45°C, 42°C (5 min) 59°C, 57°C (10 min)
6	10 ACPH	centreline	39°C, 28°C	41°C, 28°C
7	8 ACPH	centreline	49°C, 48°C	40°C, 47°C

For scenario 1 to 4, fire source in the front on the starboard side, the temperature is generally below 60 °C for the scenarios with the ventilation on. The temperature exceeds the critical value of 60 °C for the scenarios without ventilation (scenario 1 and 5). General results for scenario 1 to 4 are presented below:

- Scenario 1: At 1.9 m, the temperature exceeds 60 °C in most of the ro-ro space after 10 min.
- Scenario 2: At 1.9 m the temperature is getting close to 60 °C a few meters from the fire.
- Scenario 3 and Scenario 4: For the scenarios with reversed ventilation, the temperature is even lower than Scenario 2. The temperature is generally below 40 °C all the way to the fire. This is the best result for the temperature parameter of simulation 1 to 4.

The temperatures in scenario 1 to 4 are illustrated through screenshot from simulation model, see Figure 54 to Figure 56. In the figures the colour red represents areas where the temperature exceeds 92 °C. Our investigated limit of 60 °C is green.

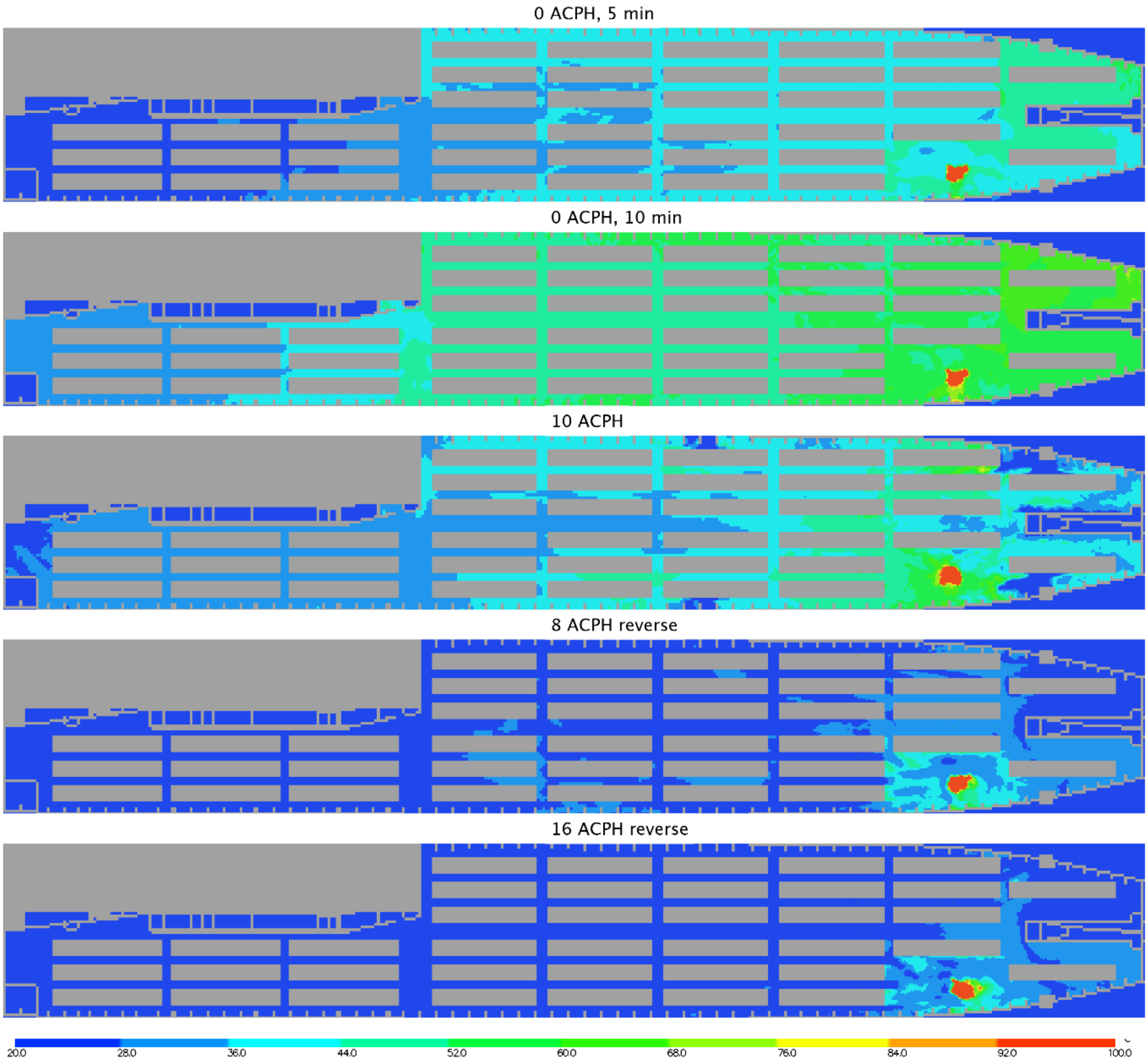
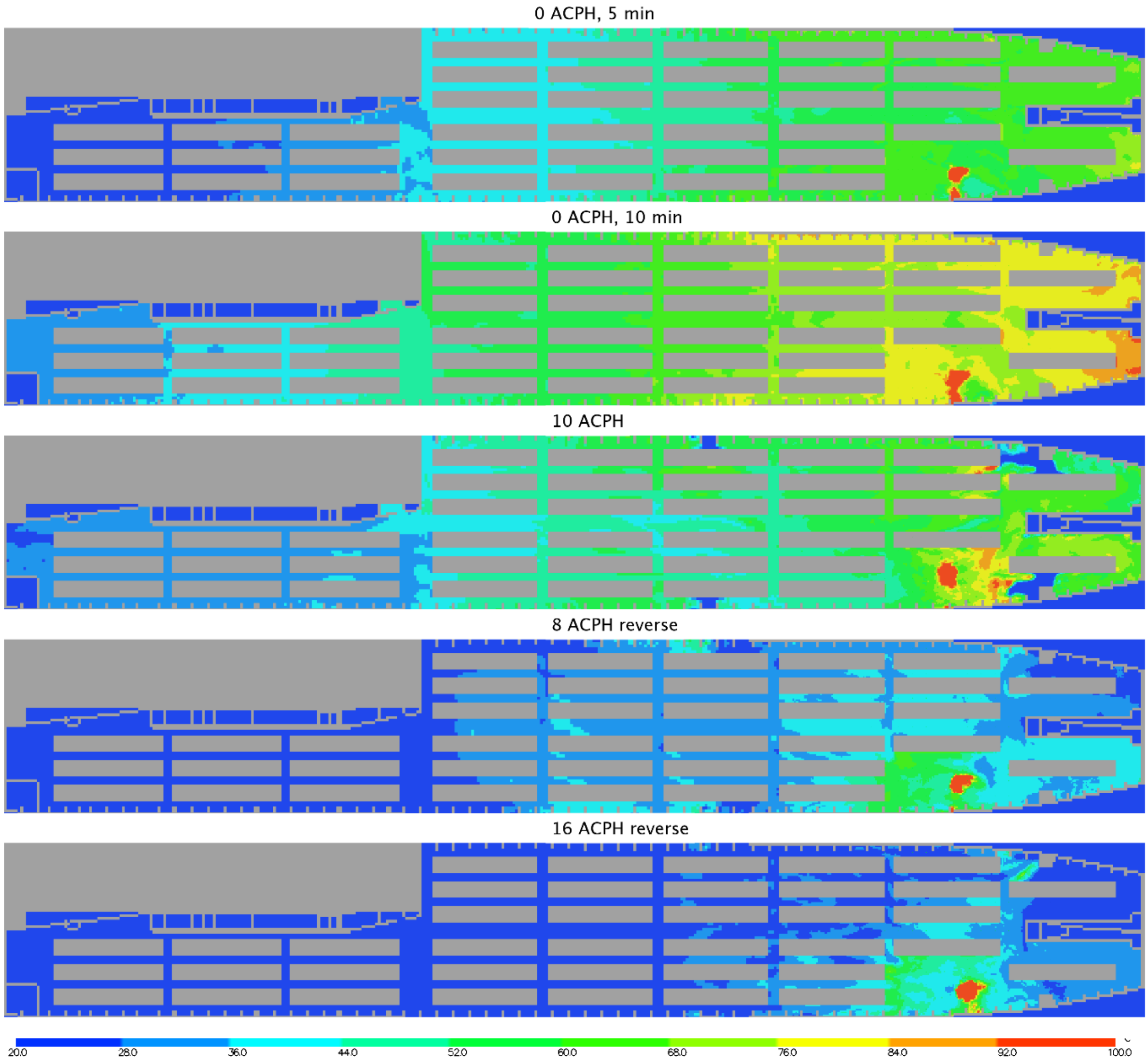


Figure 54: Temperature 1.9 m above the deck for all cases with the fire placed in the front.



0 ACPH, 5 min

0 ACPH, 10 min

10 ACPH

8 ACPH reverse

16 ACPH reverse

Figure 55: Temperature 2.9 m above the deck for all cases with the fire placed in the front.

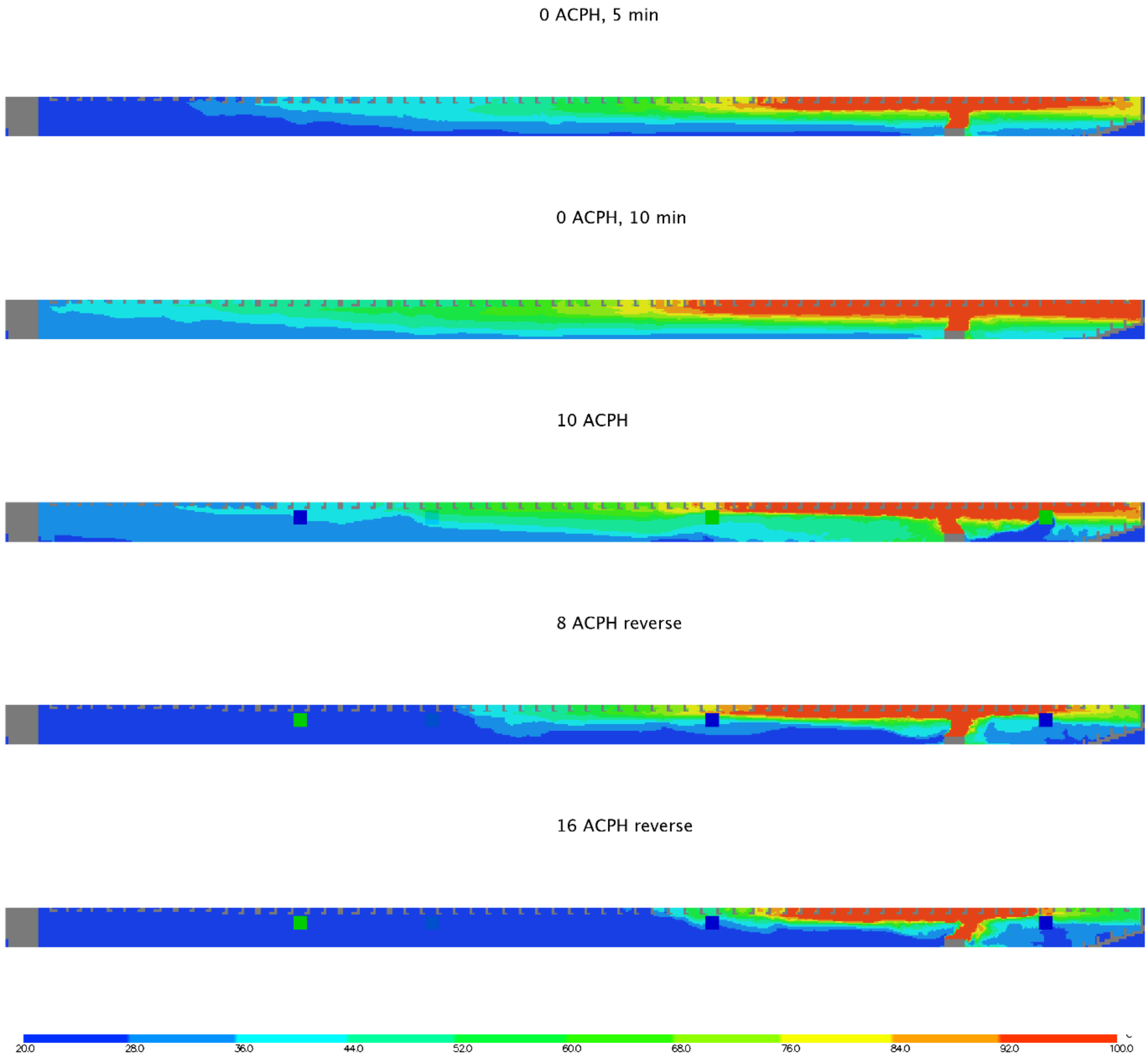


Figure 56: Temperature in a vertical plane through the fire source for all cases with the fire placed in the front.

General results for scenario 5 to 7 are presented below:

- Scenario 5: At 1.9 m height, the temperature exceeds 60°C in most of the ro-ro space after 10 min. This is similar to the results for scenario 1.
- Scenario 6: At 1.9 m the temperature is generally below 60°C a few meters from the fire. The result indicates that normal operation of the fans results in a lower temperature within the ro-ro space compared to shutting the fans off.
- Scenario 7: For reverse operation of the fans, at 1.9 m height, the temperature is generally below 60°C except direct above the fire source. The results show slightly higher temperatures compared to scenario 6. This indicates that it if a fire is located away from a supply or exhaust fan, reversible fans would not be beneficial.

The temperatures in scenario 5 to 7 are illustrated through screenshot from simulation model Figure 57 to Figure 59. In the figures the colour red represents areas where the temperature exceeds 92°C. Our investigated limit of 60°C is green.

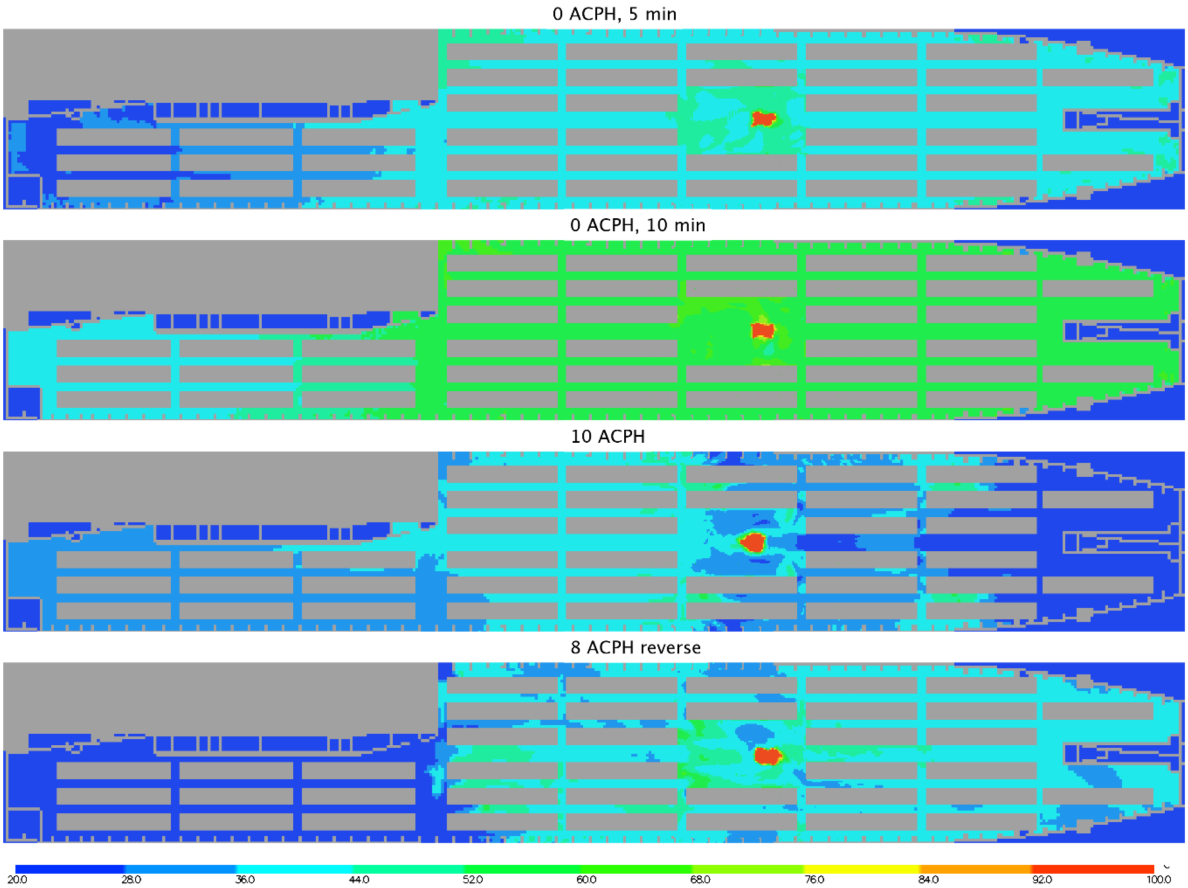


Figure 57: Temperature 1.9 m above the deck for all cases with the fire placed in the middle.

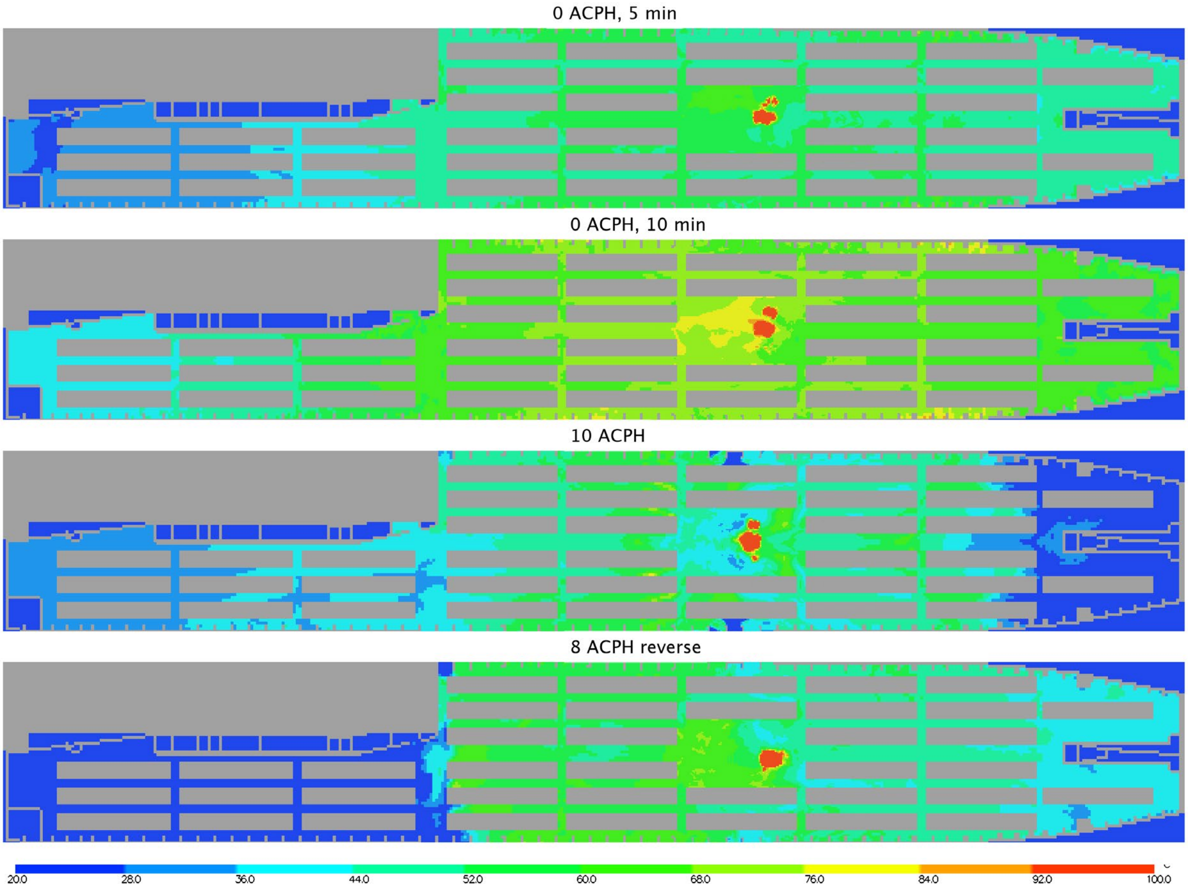


Figure 58: Temperature 2.9 m above the deck for all cases with the fire placed in the middle.

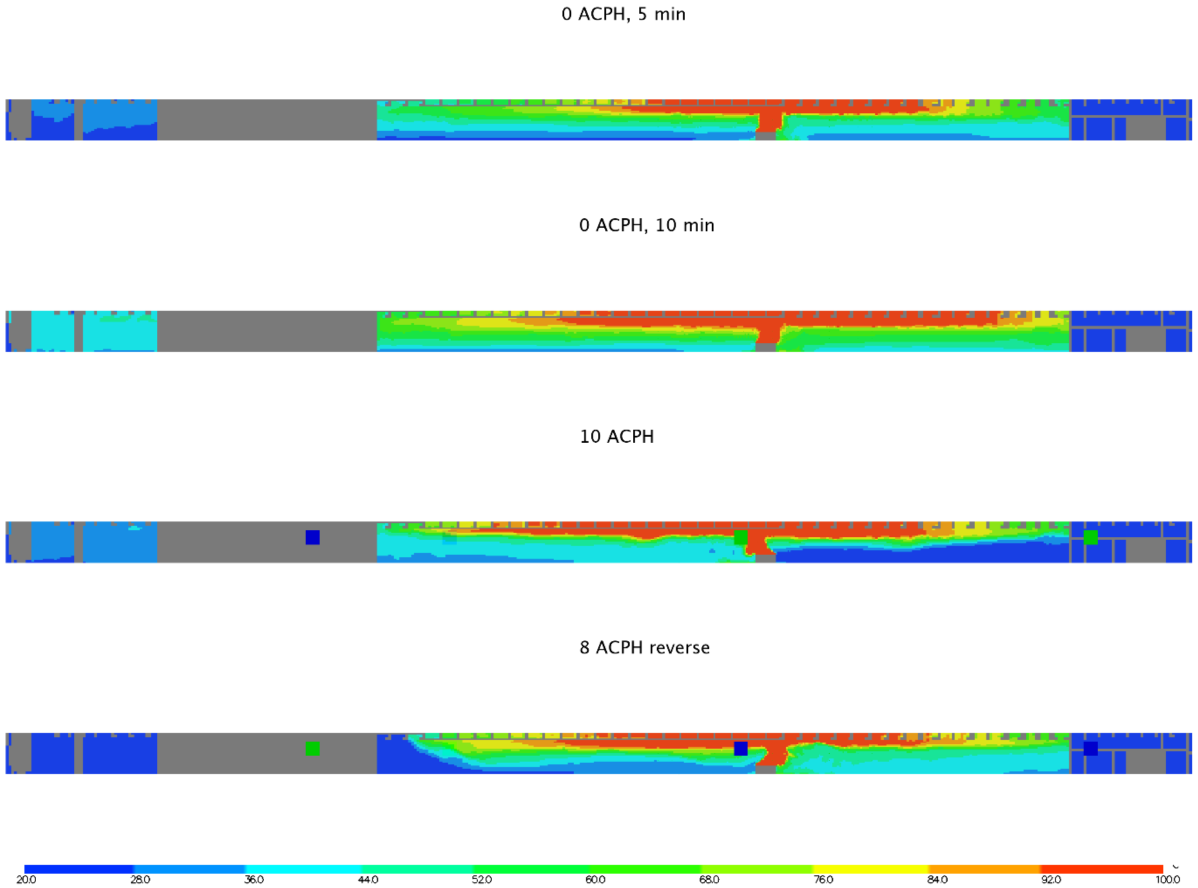


Figure 59: Temperature in a vertical plane through the fire source for all cases with the fire placed in the middle.

9.1.1.3 Incident radiative heat flux

The incident radiative heat flux has been studied by virtual sensors pointing upwards in the ro-ro space, positioned at 1.9 m above deck. The incident radiative heat flux is below 2.5 kW/m^2 at 4 m from the fire source from all directions for every scenario (1 to 7). The radiation level is rapidly decreasing with a greater distance to the fire source. The simulation results for incident radiative heat flux at pre-defined positions, 5 and 10 m from the fire upstream and downstream, are presented in Table 18.

Table 18: Simulation results for incident radiative heat flux at predefined reference points at 5 and 10 m from the fire source.

Scenario	**Ventilation**	**Fire position**	**Incident radiative heat flux 5 m from the fire (towards aft, towards forward) [kW/m^2]**	**Incident radiative heat flux 10 m from the fire (towards aft, towards forward) [kW/m^2]**
1	Off	fore	1.6, 1.5 (5 min) 1.5, 1.5 (10 min)	0.89, 0.61 (5 min) 0.88, 0.72 (10 min)
2	10 ACPH	fore	1.6, 1.2	0.83, 0.56
3	8 ACPH	fore	1.4, 1.5	0.84, 0.50
4	16 ACPH	fore	0.98, 1.7	0.56, 0.52
5	Off	centreline	1.1, 1.4 (5 min) 0.92, 1.2 (10 min)	0.51, 0.46 (5 min) 0.59, 0.53 (10 min)
6	10 ACPH	centreline	2.0, 0.76	0.71, 0.40
7	8 ACPH	centreline	1.12, 1.53	0.613, 0.455

9.1.2 Inputs taken from the simulations regarding mechanical ventilation

The outlined questions are answered below.

- *When should mechanical ventilation be considered in case of fire in a ro-ro space?*

The usage of mechanical ventilation (fans) should be assessed continuously during a fire. Overall, the usage of mechanical fire ventilation is an active tool, which needs to be adjusted to the fire scenario and be able to be started and switched off as needed [2, p. 87].

The field study supported a concept to consider the usage of mechanical ventilation in the early stages of a fire in a closed ro-ro space. This is a scenario where the fire spread has not propagated more than to a level where it is still possible to do some manual intervention. This means that the usage of mechanical ventilation is only studied for fires approximate to 5 MW.

It is noted however that the crew need to be able to assess the fire development if they should use the threshold of 5 MW in the tactics. One way could be by installing heat detectors to be used for assessing the fire development.

Another case where mechanical ventilation can be used during a fire scenario is the evacuation of smoke after the fire is extinguished. Japan has proposed smoke extraction as part of firefighting activities to IMO [38] and fire ventilation is widely used in buildings which can be done with hatches in the roof top, allowing smoke to evacuate through normal heat buoyancy. Hatches in roof tops are not present in ro-ro spaces and other means for smoke evacuation needs to be evaluated. This scenario has however not been included in this task.

A fire of 5 MW, corresponding to one car burning [39] [9], is considered a reasonable limit where manual firefighting operations can be carried out. Therefore, this study has used a 5 MW fire to investigate mechanical ventilation measures. This is also in line with the “Small fire” scenario (A2) in the LASH FIRE risk model [32].

- *Will reversible fans help the crew to do a manual intervention?*

The results presented in this report indicates that the temperature, incident radiative heat flux and visibility improve when using mechanical ventilation during a fire in a closed ro-ro space. Temperature and radiant heat flux is below the defined performance criteria when mechanical ventilation is used.

Positive effects are clearly seen for temperature, where mechanical ventilation makes the temperature stay below the critical value of 60 °C. The incident radiative heat flux is below 2.5 kW/m^2 at 4 m from the fire source from all directions for every scenario. Visibility of 10 meters is only achieved 10 m from the fire in a scenario where the fire is close to an exhaust fan with 16 ACPH.

It should be noted that the simulations have been made based on the assumption that the fixed water based “drencher” system has not been activated.

9.1.3 Discussion on simulation result

The simulations performed in this study show that the use of mechanical ventilation during a 5 MW car fire in a closed ro-ro space decreased the temperature of the air surrounding the fire. This indicates that using the mechanical ventilation can have a positive effect on the air temperature during manual firefighting operations. Benefits of having reversible fans were seen when the fire was located close to a supply fan, reversed into an exhaust fan. When the fire was located away from the fans, no benefits could be seen by having reversible fans.

The incident radiative heat flux did not exceed the critical value of 2.5 kW/m^2 within 5 m from the fire source for any studied scenario. This indicates that the incident radiant heat flux is not the most crucial of the studied parameters for the conditions for manual firefighting operations of a single burning car.

The visibility was the restricting parameter. The simulation results showed that using mechanical ventilation during a 5 MW car fire reduced the smoke within the closed ro-ro space, which in turn improved the visibility. The results indicate that mechanical ventilation reduces the smoke within the closed ro-ro space and improves visibility, but not necessarily to an extent that would facilitate manual firefighting operations.

9.1.4 Conclusion from computer simulations on mechanical ventilation

Main author of the chapter: Stina Andersson, RISE

How to use the mechanical ventilation in a closed ro-ro space in case of a fire is an area in need of clarification. The current lack of clear guidance on how to use the mechanical ventilation is an issue. Fans are already used in firefighting operations in land-based applications, and use of fans are seen as a potential way of facilitating manual firefighting onboard ro-ro ships.

It can be concluded that reversible fans were beneficial, compared to normally operated fans, in case the fire is located close to a supply fan that could be reversed to an exhaust fan. Additional testing is needed to support the simulation results and further examine the effects of mechanical ventilation.

The results in this study indicate that mechanical ventilation could facilitate manual firefighting in the early phase of a fire in a closed ro-ro space. When a fire inside a closed ro-ro space exceeds 5 MW, the current praxis of shutting down the ventilation and activate the extinguishing system is not challenged. Visibility of 10 m can be achieved with 16 ACPH and fire located in the fore part.

It should be noted that the effects on fire spread have not been studied by computer simulations in this report.

9.1.4.1 Visibility

Regarding visibility for a fire located in the fore part the best conditions are caused with reverse operation of the fans with 16 ACPH. The simulations indicate that a visibility of 10 m can be achieved at a distance of 10 m from the fire source, this is better than 8 and 10 ACPH and also better than having fans off. Within 10 m from the fire source, the visibility decreases below 10 m.

For a scenario where the fire is located in the centre part of the ship the best scenario is when the ventilation is on, 8 or 10 ACPH does not make a big difference. The smoke is thinner downstream than upstream of the fire in both cases. The visibility downstream of the fire source is approximately 5-10 m for a reflective sign for both scenario 6 and 7. This is the best result for the visibility and the fire located in the centre part.

9.1.4.2 Temperature

With a fire source in the front the temperature at 1.9 m height is generally below 60 °C for the scenarios with the ventilation on. The temperature exceeds the critical value of 60 °C for the scenarios without ventilation after approximately 10 min.

For the scenarios with reversed ventilation (8 ACPH and 16 ACPH), the temperature is even lower than with normal ventilation. The temperature is generally below 40°C all the way to the fire. This is the lowest result for temperature in scenarios with a fire in the front (scenario 1 to 4). This result indicates that if a fire is located close to a supply fan, it is beneficial to be able to reverse it into an exhaust fan.

With a fire in the centreline the temperature exceeds 60°C in most of the ro-ro space after 10 min when the ventilation is off. This is similar to the results for a fire in the front and no ventilation.

9.1.4.3 Incident radiative heat flux

The incident radiative heat flux is below the threshold of 2.5 kW/m^2 at 4 m from the fire source from all directions for every scenario (1 to 7). The radiation level is rapidly decreasing with a greater distance to the fire source.

9.2 Model scale tests

Main authors of the chapter: Stina Andersson, RISE.

The mechanical ventilation test series was made to investigate the effects of using mechanical ventilation during a fire in a closed ro-ro space. The aim with the test series was to evaluate if, and how, the mechanical ventilation can be used to facilitate manual firefighting inside closed ro-ro spaces.

The specific safety measure studied was reversible fans in closed ro-ro spaces. It was studied if and how this can improve the manual firefighting operations by improving the environmental conditions (visibility, temperature, smoke layer height, radiation) for the crew, and by creating a possibility to control the spread of smoke in the ro-ro space. A fire of 5 MW, corresponding to one passenger car burning [8] [9], is considered a reasonable limit where manual firefighting operations can be carried out. Therefore, a fire of 30 kW, which scales up to a 5 MW fire, has been used in the mechanical ventilation tests.

Wood was used as the primary fuel in the tests. Wood was considered more stable fuel compared to heptane and therefore set to the primary fuel type for mechanical ventilation tests.

The total amount of energy (integrated heat release rate curve) measured by the hood calorimeter during the free burning test for wood crib was 37 MJ. For the model scale tests, the HRR was measured using both the weighing platform and the hood calorimeter (see 7.3.1). The total energy released has been calculated for all tests and the results are presented in Table 19.

Table 19. Total energy for tests with mechanical ventilation using wood crib as a fuel and free burning test.

Scenario number	Initial weight wood crib (g)	Humidity (%)	Total Energy (MJ) Hood	Total Energy (MJ) Weight
Free burning wood crib	No data	No data	37	N/A
2-1	2299	9	N/A	25
2-3	2305	8.5-9.2	25	32
2-5	2386	8.5-9.2	28	N/A
2-6	2345	8.5-9	27	N/A
2-7	2214	8.5-9.2	27	34
2-8	2312	8.6-9.2	25	N/A

2-9	2323	8.6-9.4	18	N/A
2-13	2344	8.5-9	N/A	32
2-14	No data	8.7-9.2	N/A	33
2-15	33097	8.7-9.5	N/A	389

The energy calculations show that the total energy measured by the hood is generally lower for the model scale test compared to the free burning test. Since the hood calorimeter measures HRR based on the amount of oxygen in the analysed air (see 7.3.2), this difference could be due to the fact that not all smoke was being led from the model into the hood. This can possibly be due to leakage in the model, as well as other parts of the duct system between the model and the hood. There could also be smoke left in space (i.e. the model) creating a delay in the transport that may be missed at the end of the test when measurements were stopped. The hood system measurements were stopped at around 25 minutes.

The abovementioned could also explain why the total amount of energy is lower for the hood measurement compared to the weighing platform measurement for the tests that used both methods to measure HRR (test 2-3 and test 2-7).

9.2.1 HRR analysis

Test 2-7 shows the most intense HRR of the test scenarios, according to both scale and hood HRR measurements. This means that the highest HRR is seen when the fire is located in section 6 and fans are on with 20 ACPH.

Figure 60 shows the HRR for the free burning test compared with the reference case (2-1), test 2-3, test 2-7 and test 2-13.

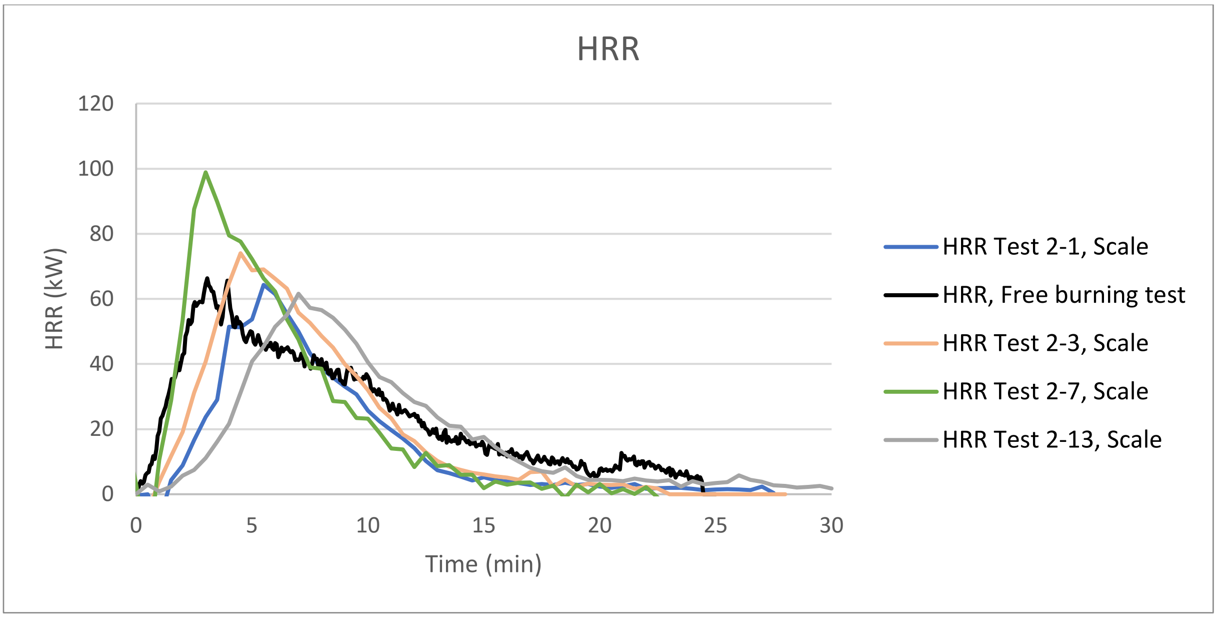


Figure 60: HRR comparison between free burning test, test 2-1, 2-3, 2-7 and 2-13, measured with weighing platform (marked scale).

The reason for the initial delay in the fire growth in Figure 60 in model tests compared to free burning test is most likely due to the process from ignition until the fire starts to spread within the wood crib which was slower inside the model. After the fire spread is established within the wood crib the fire growth rate is similar.

Test 2-3 shows lower HRR values compared to test 2-7. A possible explanation is that 10 ACPH was used for test 2-3 and 20 ACPH for test 2-7. This indicates that the ventilation rate may have influenced the HRR development in such a way that higher HRR was obtained.

Test 2-6 shows lower peak HRR compared to test 2-7. Having the fire located further away from the supply fan may have reduced the HRR compared to having the fire close to the supply fan. Also, the ACPH was slightly lower in test 2-6 (16 ACPH) which may have reduced the HRR.

Tests 2-1 and 2-13 are similar, but 2-13 is a bit delayed and seem to have a slower heat release rate. In test 2-13 the fan was shut off, but the end was open. This may explain the delayed fire development.

Figure 61 shows the HRR for test 2-15 and compares it to the HRR from the free burning test as well as the test in the natural ventilation test series using the large wood crib, i.e. test 1-3 and 1-5. Although test 2-15 belongs to the mechanical ventilation test series, the test was performed without any mechanical ventilation and with the same size of fire size as natural ventilation test series. It is therefore interesting to compare the result to the natural ventilation tests.

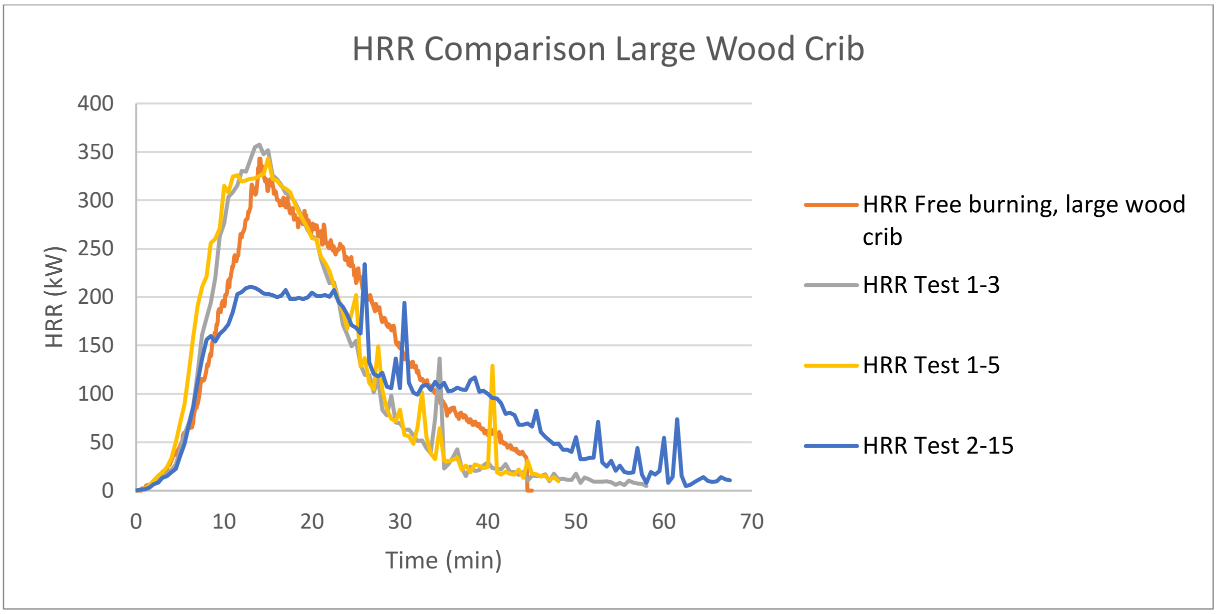


Figure 61: HRR comparison between free burning test for large wood crib, mechanical ventilation test 2-15 and natural ventilation test 1-3 and 1-5. HRR measured with weighing platform (marked scale) for all model scale test and with hood for the free burning test.

The difference between the test scenarios is that test 2-15 does not have any side openings. In other words, test 2-15 have fewer openings for natural ventilation compared to test 1-3 and 1-5. Figure 61 shows that the peak HRR is lower when there are no side opening present. It should be noted that the total amount of energy in the model tests are as follows: 411 MJ for free burning test, 389 MJ for test 2-15, 312 MJ for test 1-3 and 288 MJ for test 1-5. Although the total energy is highest for test 2-15, the HRR is the lowest for the initial 20 minutes. This indicates that closing the side opening reduces the HRR, and thus reduces the intensity of the fire. Although the intensity of the fire is reduced in the test scenario without side openings, the fire does not show signs of self-extinguishing.

9.2.2 Temperatures

A good indicator of the HRR is the measured (outside) steel temperature above the fire source. In Figure 62 such measurements are shown above fire source in section 6 and in section 9/10, respectively. Wood crib was used as fuel in these scenarios.

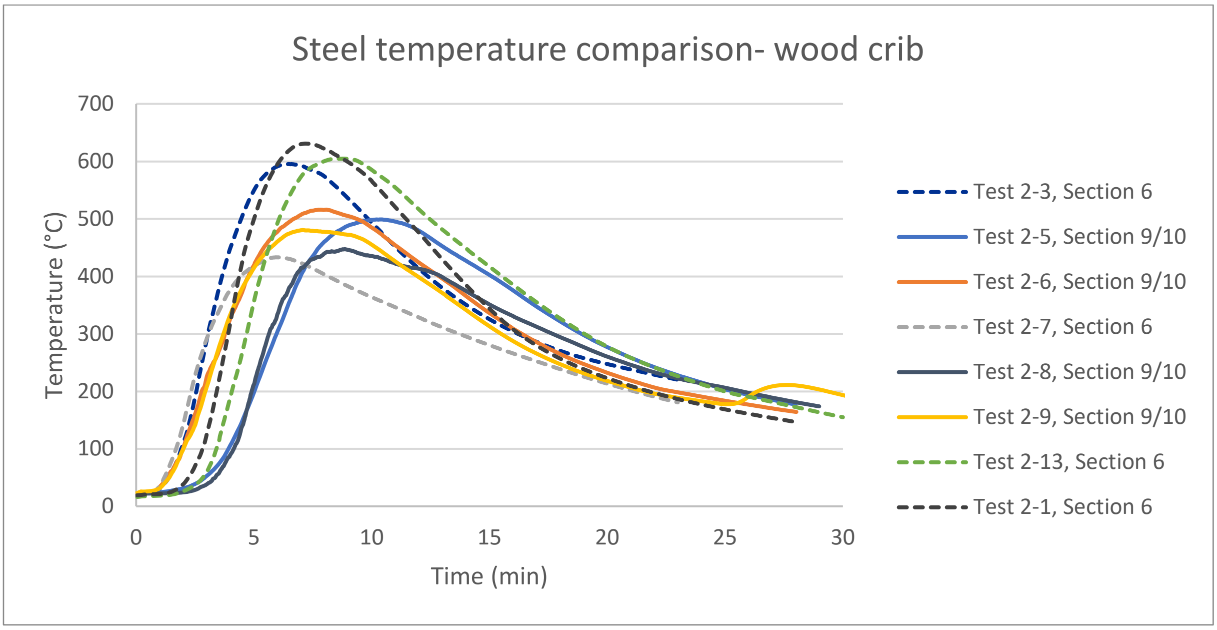


Figure 62: Steel temperature above the fire for mechanical test scenarios using wood crib as fuel. Data is from Section 6 (dashed lines) and Section 9/10 (solid lines).

The steel temperature is measured above each fire position. It is clear that the highest steel temperatures are seen for tests 2-1, 2-3 and 2-13 with the fire location at section 6, which is about at the middle of the model. The common conditions for these tests are fire position and fan setting (10 ACPH). One end is open in test 2-13 but not in tests 2-1 and 2-3. Test 2-7 has higher fan setting, 20 ACPH, and the steel temperature is reduced considerably, by 150 – 200 ℃. The steel temperatures measured above the fire in section 9/10 are about 100 – 150 ℃ lower than steel temperatures in section 6. This is true for tests 2-5, 2-6, 2-8 and 2-9. The largest reduction is seen for 20 ACPH when the fire is located in the middle of the model (test 2-7). The steel temperature is mainly influenced by the ventilation rate and the location of the fire.

Figure 63 shows the steel temperature in section 6 for test 2-15 and compares it to the steel temperature measured during the test in the natural ventilation test series using the large wood crib, i.e. test 1-3 and 1-5.

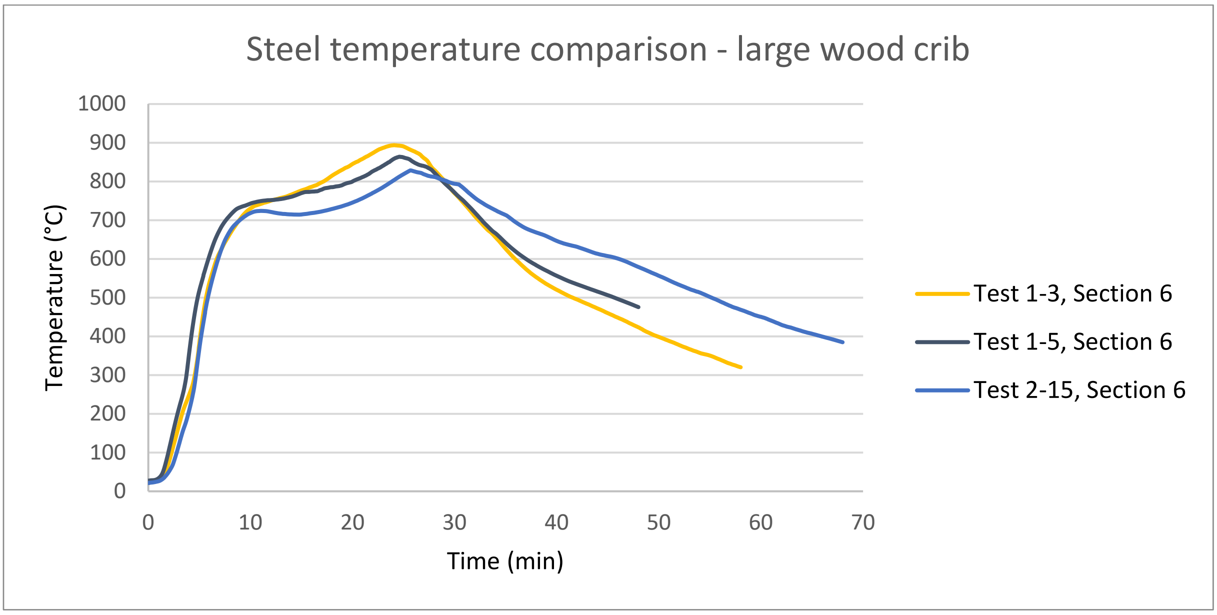


Figure 63: Steel temperature above the fire for mechanical test scenarios using large wood crib as fuel, data from Section 6.

Figure 63 shows that the steel temperature directly above the fire is lower for test 2-15 than for test 1-3 and 1-5 during the initial 20-25 minutes. This is in line with the HRR comparison showed in Figure 61 and supports the discussion that closing the side opening reduces the intensity of the fire.

The temperature data from the plate thermocouples, PT, was used to compare and analyse inside temperature for the mechanical ventilation tests.

A comparison of the PT temperature in the test scenarios where the fan capacity is similar, but the fire is either located in between the supply and exhaust fans (test 2-3 and test 2-7) or located closer to the exhaust fans (test 2-5 and test 2-6) is presented in Figure 64 and Figure 65.

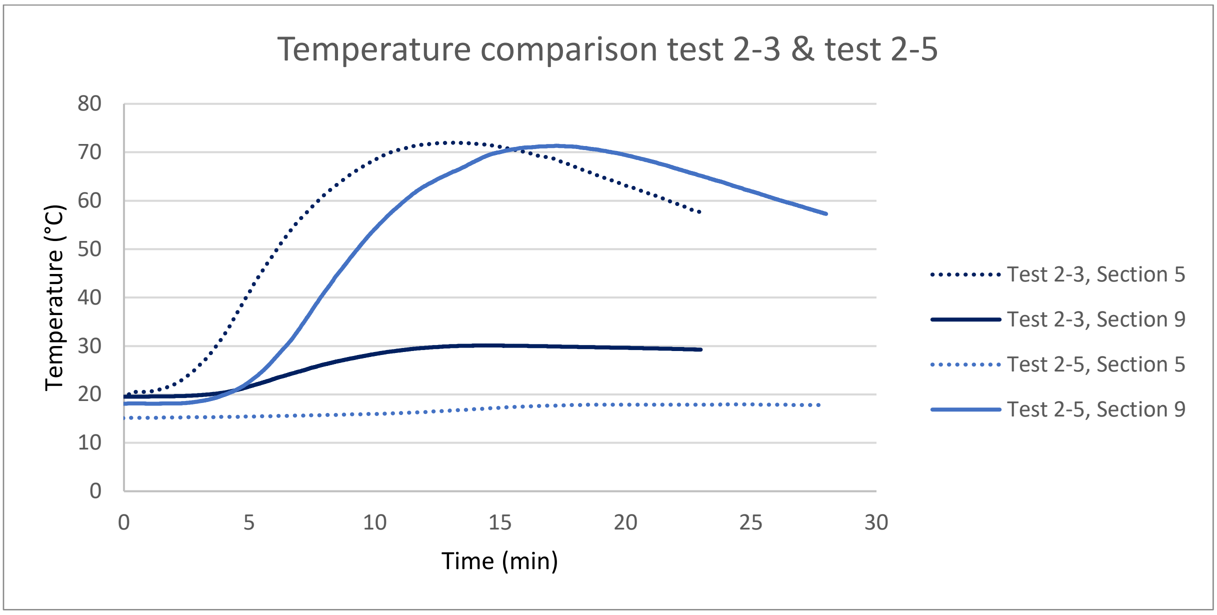


Figure 64: PT temperature comparison for test 2-3 and 2-5. Data is from PT in Section 5 (dotted lines) and PT in Section 9 (solid lines).

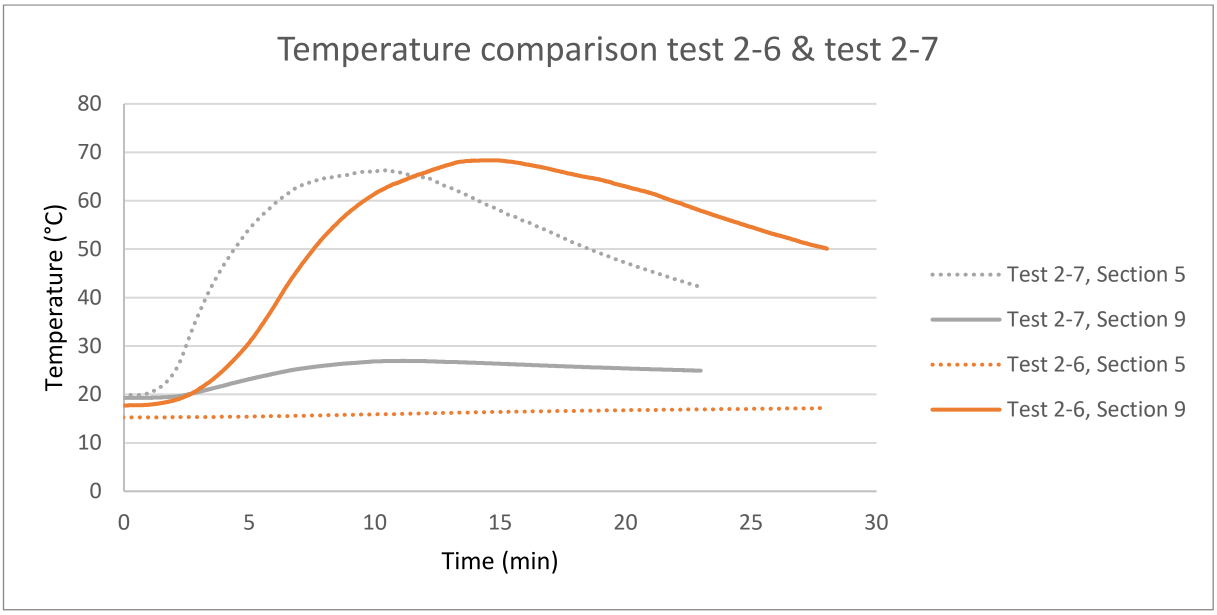


Figure 65: PT temperature comparison for test 2-6 and 2-7. Data is from PT in Section 5 (dotted lines) and PT in Section 9 (solid lines).

The comparison shows that the PT temperature upstream the fire increases when the fans are used. The highest temperatures are seen for 8 and 10 ACPH (test 2-3 and 2-5), independent if the fire location. Slightly lower PT temperatures are seen when the ACPH is increased to 16 and 20 ACPH (test 2-6 and 2-7).

A comparison of the PT temperature for the reference case where both short ends are closed, test 2-1, and a test where the fans are off, but one short end is open, test 2-13, is shown in Figure 66.

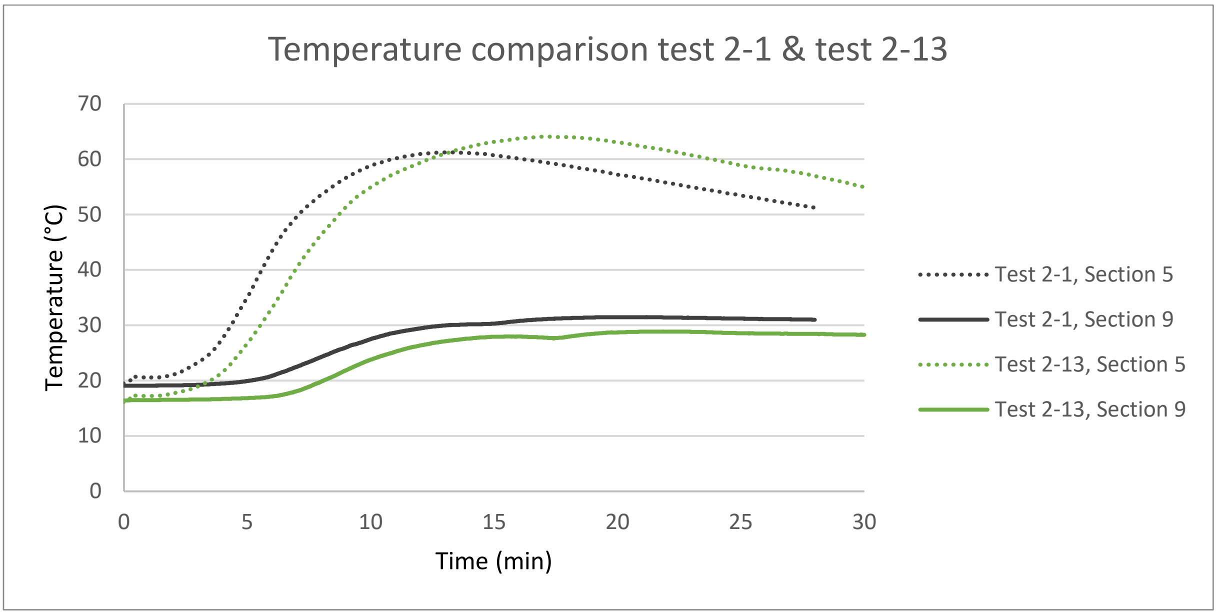


Figure 66: PT temperature comparison for test 2-1 and 2-13. Data is from PT in Section 5 (dotted lines) and PT in Section 9 (solid lines).

As expected, the PT temperatures are higher in the section closest to the fire compared to the section further from the fire. When comparing the PT temperatures in the sections closest to the fire, there is no significant difference between the scenarios. The comparison of the tests 2-1 and 2-13 shows that keeping the fans on inside the ro-ro space will increase the temperature of the gas due to better ventilation. This is in line with what was observed when analysing the HRR data.

When comparing the temperatures in the sections furthest from the fire, it is clear that the test scenarios where the PT is located upstream of the air flow (test 2-1, 2-3 and 2-7) show higher temperatures compared to the test scenarios where the PT is located downstream of the air flow (test 2-5 and 2-6).

The measured PT temperatures are higher for tests 2-5 and 2-6 compared to tests 2-1, 2-3 and 2-7. However, there is an uncertainty regarding T_∞ in Equation 10 due to different distances between. The temperature measurement points. This uncertainty should be considered when reviewing the results above.

9.2.3 Light transmission through smoke analysis

The light transmission through smoke was used to analyse smoke density in the space. Light transmission is a measure of how much of the laser that hits the receiver, i.e., the fraction of the light that is transmitted to the receiver. The light transmission is dimensionless.

Light transmission through smoke for scenarios where the wood crib was positioned in Section 6 are presented in Figure 67.

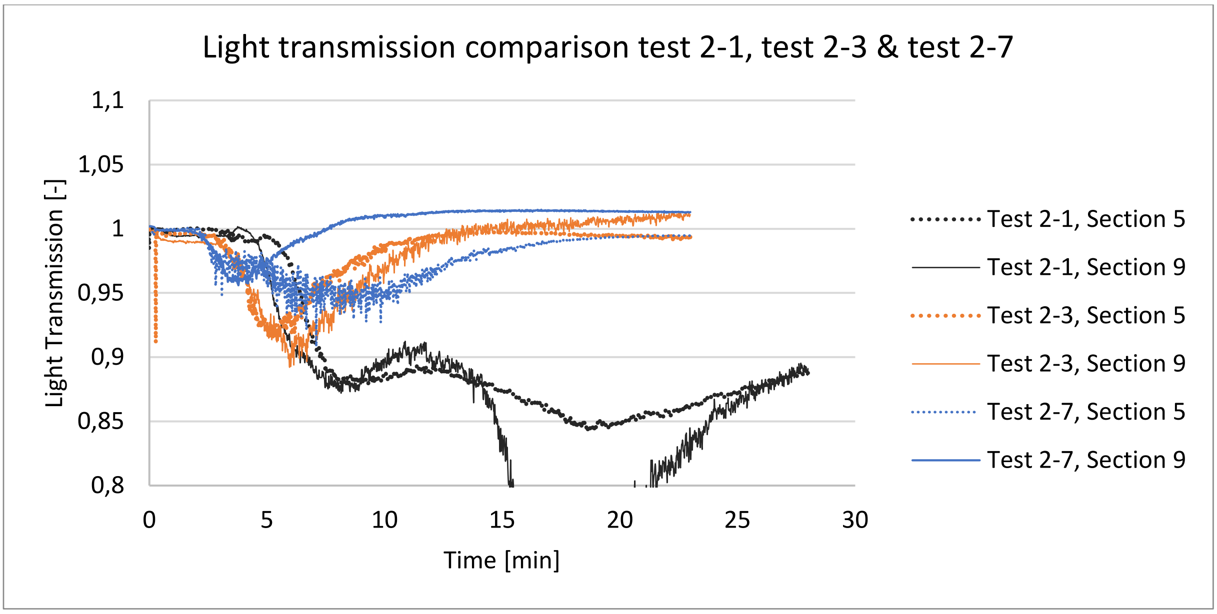


Figure 67: Light transmission through smoke comparison for tests 2-1, 2-3 and 2-7. Data is from laser in Section 5 (dotted lines) and in Section 9 (solid lines).

The results show that the reference case, test scenario 2-1, gave the highest smoke density. The results show that when the fans were active and the fire is located at similar distance to the supply and exhaust fans, lower smoke density is obtained compared to the reference case, both in section 5 and section 9. In section 5, there is no significant difference between fan capacity 10 ACPH and 20 ACPH. In section 9, the results show that 20 ACPH gives less smoke density compared to 10 ACPH. In only one case, test 2-1, the smoke density becomes less in section 9. As this is a single test, and not possible to identify any clear explanation, this phenomenon can be regarded as a local and sudden behaviour during this test. It is although clear that smoke is transported to this part of the model.

Light transmission for the test scenarios with fire position in Section 9/10 of the model and active fans were active during the whole test is presented in Figure 68.

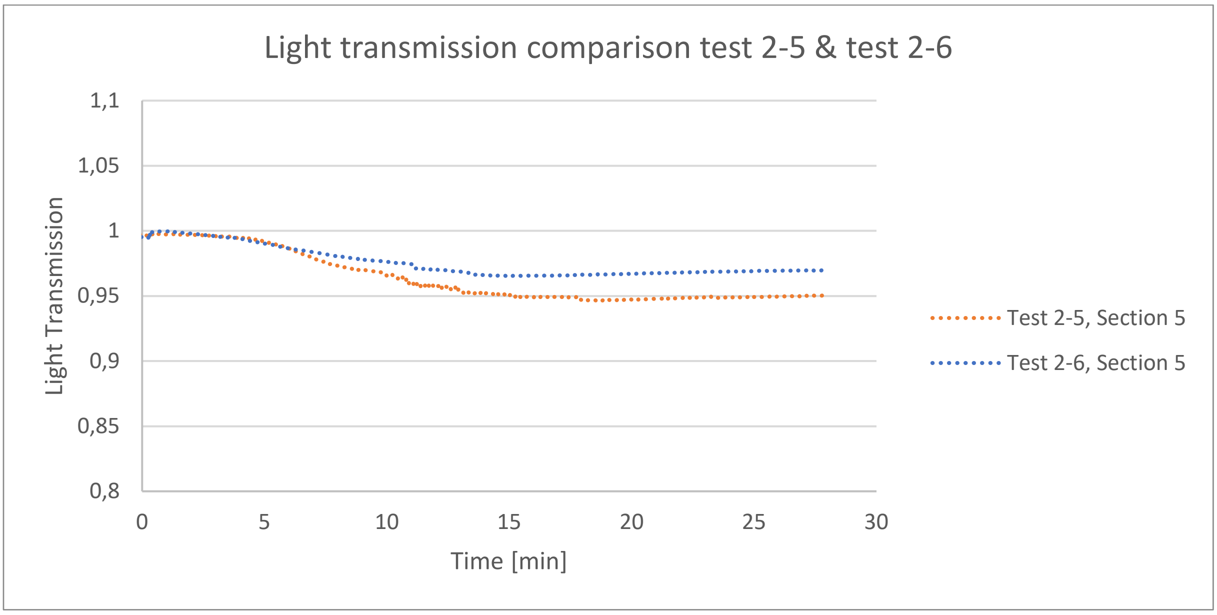


Figure 68: Light transmission through smoke comparison for test 2-5 and test 2-6. Data is from Section 5 (dotted lines).

The results show that maintaining the fans active when the fire is located close to the exhaust fan gives better light transmission through smoke compared to the reference case in section 6 (test 2-1).

Light transmission through smoke for the test scenarios where the wood crib was placed in Section 9/10 of the model and where fans were activated a time after fire ignition are presented in Figure 69. The difference between the test scenarios is only when the fans were activated. In test 2-8, the fans were started at 3.5 minutes (blue vertical line). In test 2-9, the fans were started at 21 minutes (orange vertical line).

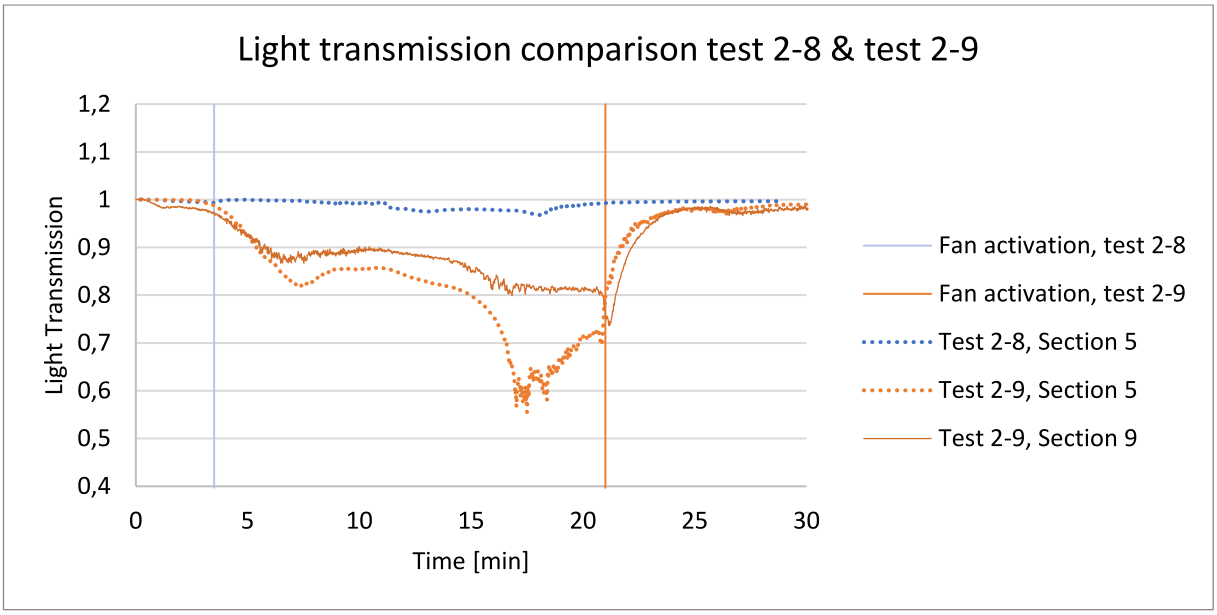


Figure 69: Light transmission through smoke comparison for test 2-8 and test 2-9. Data is from Section 5 (dotted lines) and Section 9 (solid lines). Vertical lines show when fans were activated.

The result show that an early activation of fans gives higher light transmission throughout the test, while waiting with activating fans result in decreased light transmission. When fans are activated in test 2-9, it results in improved light transmission.

A comparison of the light transmission for the reference case test 2-1 and test 2-13 is shown in Figure 70. The fire is located in section 6 and the differences between these two tests are the open end in test 2-1 and that fans are shut off at 3.5 minutes. Test 2-13 have closed ends and no active fans.

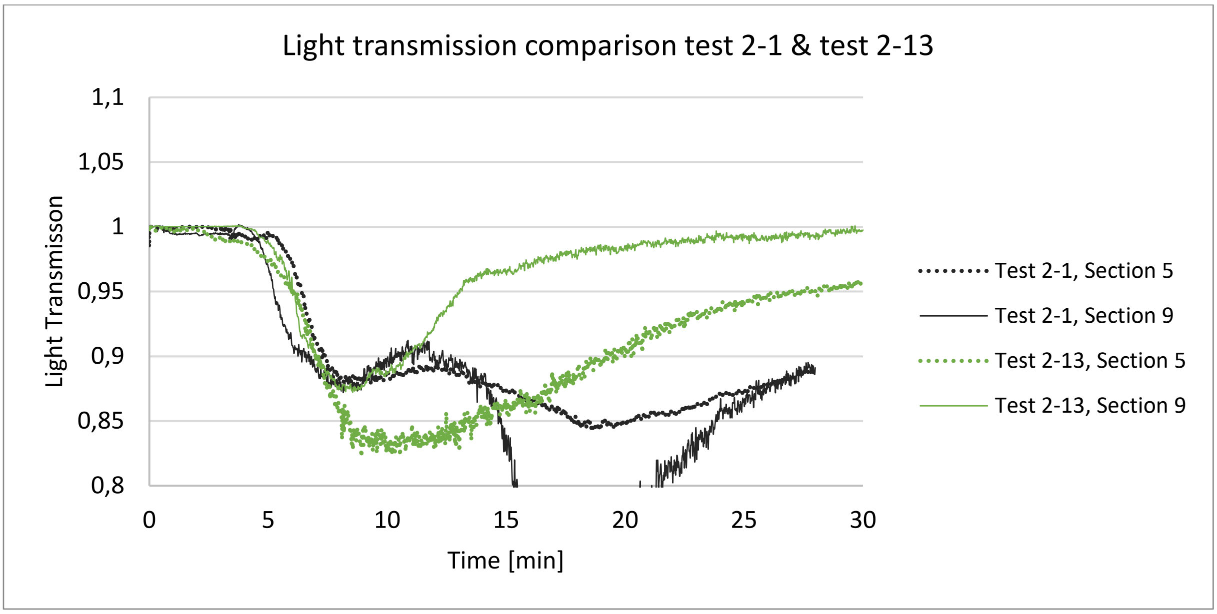


Figure 70: Light transmission through smoke comparison for test 2-1 and test 2-13. Data is from Section 5 (dotted lines) and Section 9 (solid lines).

The results show that there is no effect of keeping fans on during the first 3.5 minutes. Light transmissions are decreasing for both scenarios. The open end in test 2-13 gives result after 10 minutes which is indicated by the increased light transmission.

A comparison of the light transmission levels for the reference case test 2-1 (located in section 6) where the fans are shut off after 3.5 min, and test 2-9 (located in section 9/10) where the fans are off initially and activated after 21 minutes is shown in Figure 71.

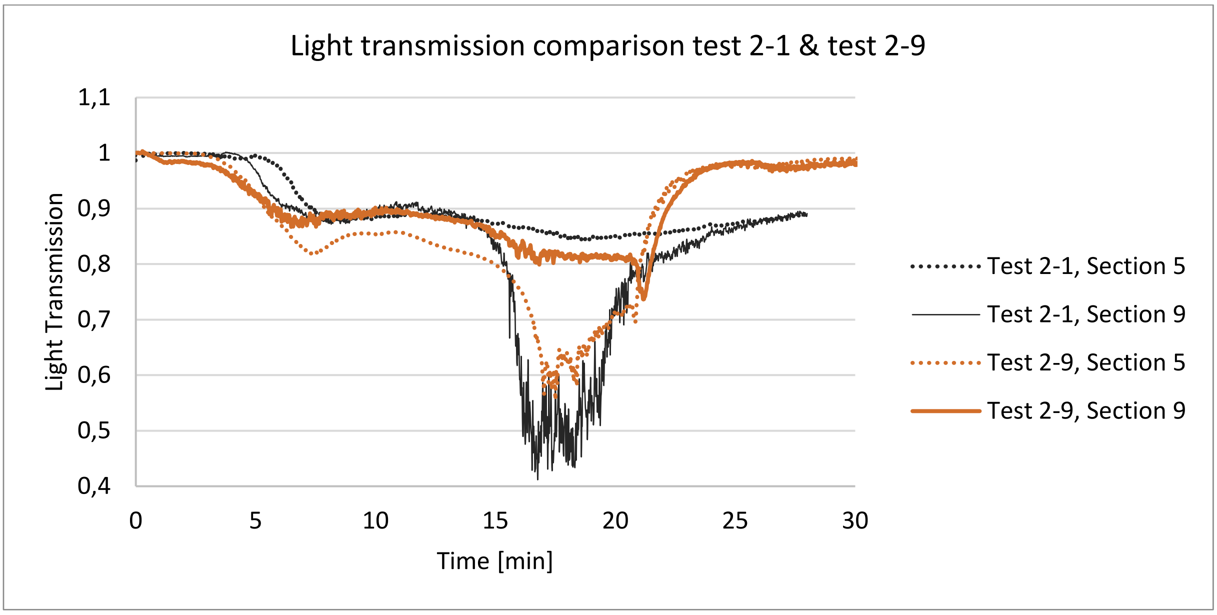


Figure 71: Light transmission through smoke comparison for test 2-1 and test 2-9. Data is from Section 5 (dotted lines) and Section 9 (solid lines).

The comparison shows that the light transmission drop that occurs around 15 minutes in test 2-1 also occurs in test 2-9 around the same time. For both test 2-1 and test 2-9, the drop occurs in the section furthest from the fire. The drop does not occur in the section closest to the fire.

The results show that the smoke density increases for the test scenarios where the fans are not active. Using fans during the fire decreases the smoke density.

9.2.4 Radiation analysis

Graphs in this section shows the radiation calculated using data from PT and TC. Incident heat flux is denoted "radiation" throughout this section. The presented results are not scaled unless this is explicitly stated in the text.

Scenarios where the wood crib was positioned in Section 6 are presented in Figure 72. The differences between the test scenarios are if the fans were active and which fan capacity was used, see Table 13.

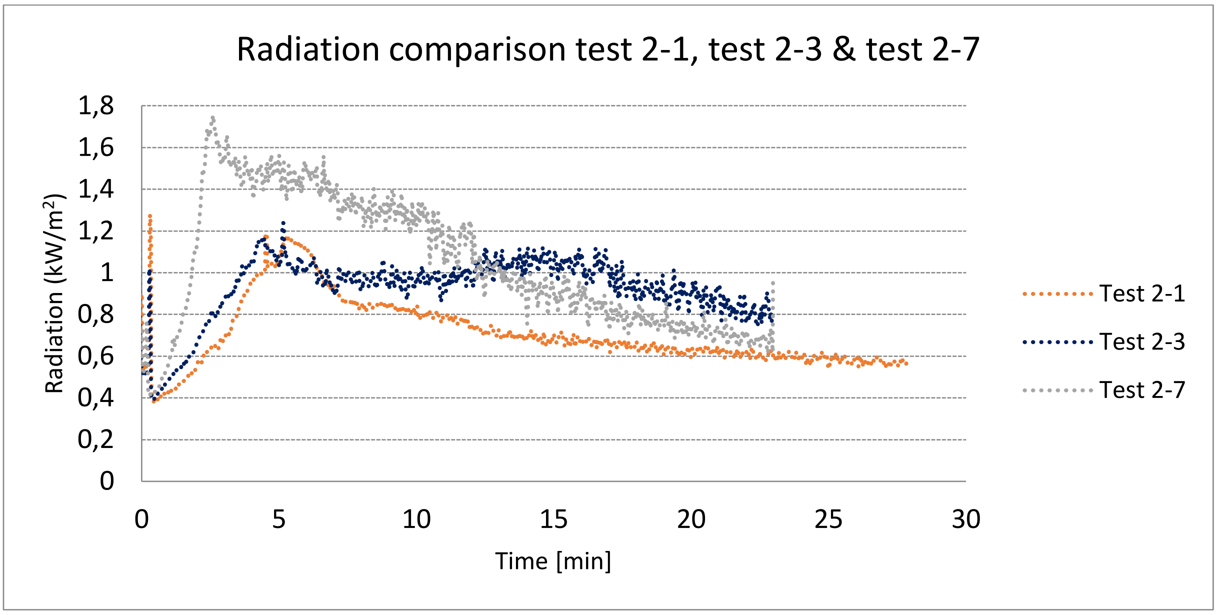


Figure 72: Radiation comparison for test scenario 2-1, 2-3 and 2-7. Data is from PT and thermocouple located in Section 5 (dotted lines).

The results show that the reference case, test scenario 2-1, gave the lowest radiation levels. Having active fans at 10 ACPH, test scenario 2-3, resulted in similar maximum radiation as the reference case, but higher radiation throughout the test. Having active fans at 20 ACPH, test scenario 2-7, gave the highest radiation levels. The comparison shows that using fans does not reduce radiation when fire is located in between supply and exhaust fans. When comparing the test scenarios where the fan capacity is similar, but the fire is either located with similar distance to the supply/exhaust fans (test 2-3 and test 2-7) or located closer to the exhaust fans (test 2-5 and test 2-6), it shows that the radiation is lower during the first 10-15 minutes of the fire, if fans are used, when the fire is located closer to the exhaust fans.

Radiation for all test scenarios where the wood crib was placed in Section 9/10 of the model are presented in Figure 73.

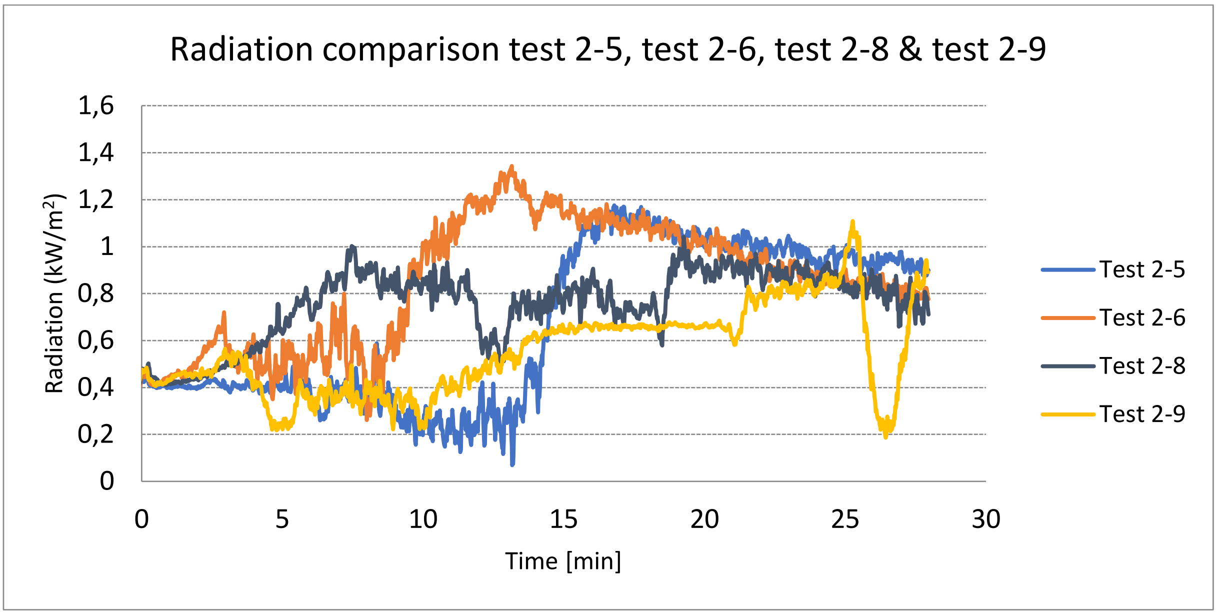


Figure 73: Radiation comparison for test scenarios 2-5, 2-6, 2-8 and 2-9. Data is from PT and thermocouple located in Section 9 (solid line).

The results show that having active fans at 8 ACPH from start (test 2-5) resulted in lower radiation compared to having active fans at 16 ACPH from start (test 2-6). During the first 10 minutes the radiation levels are lower compared to the reference case, 2-1, where fans are off after 3.5 minutes (see Figure 72). The results presented in Figure 73 show that a higher fan capacity results in higher radiation levels.

An increase in the radiation can be seen in test 2-9, where the wood crib was placed in Section 9/10 of the model, when the fans are started at 21 minutes, see Figure 74.

An increase in the radiation can be seen in test 2-9 when the fans are started at 21 minutes.

The results show that the lowest radiation level in the initial 10 minutes is achieved for the test scenario with the fans off (test 2-9) and the test scenario with fans at 8 ACPH (test 2-5). The overall results indicate that using the fans does not improve the radiation. On the contrary, active fans seem to result in higher radiation levels compared to having the fans off.

A comparison of the radiation levels for the reference case where both short ends are closed, test 2-1, and a test where the fans are off, but one short end is open, test 2-13, is shown in Figure 74.

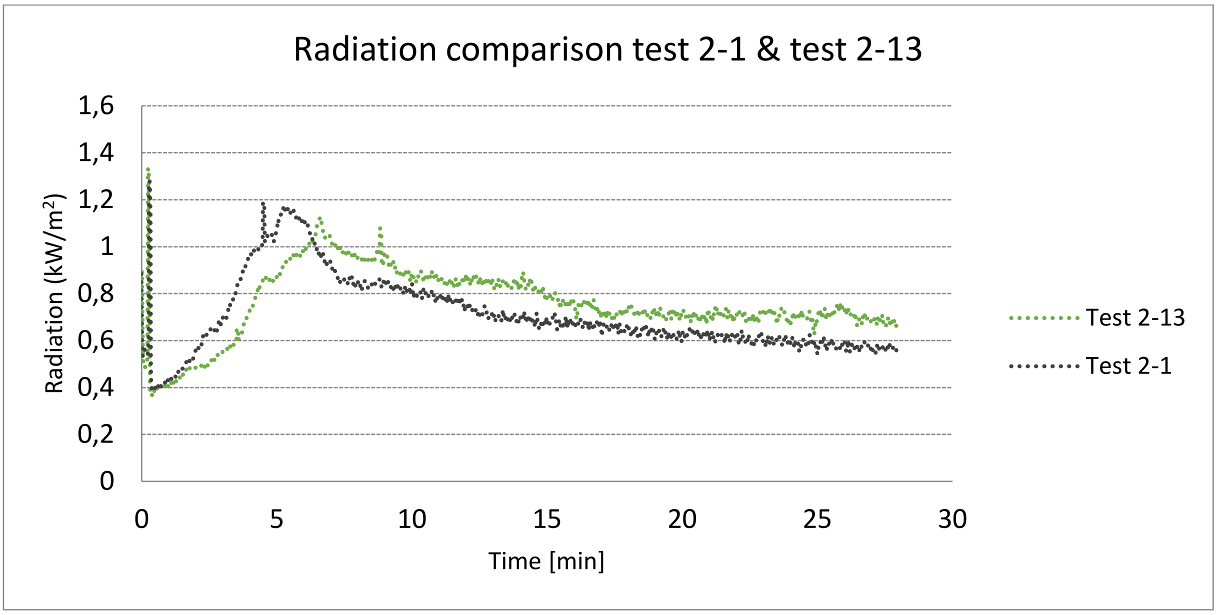


Figure 74: Radiation comparison for test scenarios 2-1 and 2-13. Data is from PT and thermocouple located in Section 5 (dotted line).

The results show similar radiation levels throughout the two tests. The peak radiation occurs later when there is one short end open compared to having both side openings closed. After the peak, the radiation levels are slightly higher for the test with one short end open compared to the test with both short ends closed.

There is a radiation peak in the beginning of several of the tests presented in Figure 72 to Figure 74. A possible reason for this peak could be an effect of the ignition stick and the closing of the hatch.

A summary of the peak radiation from the mechanical ventilation tests is presented in Figure 75. These values have been scaled using the scaling law presented in Table 10.

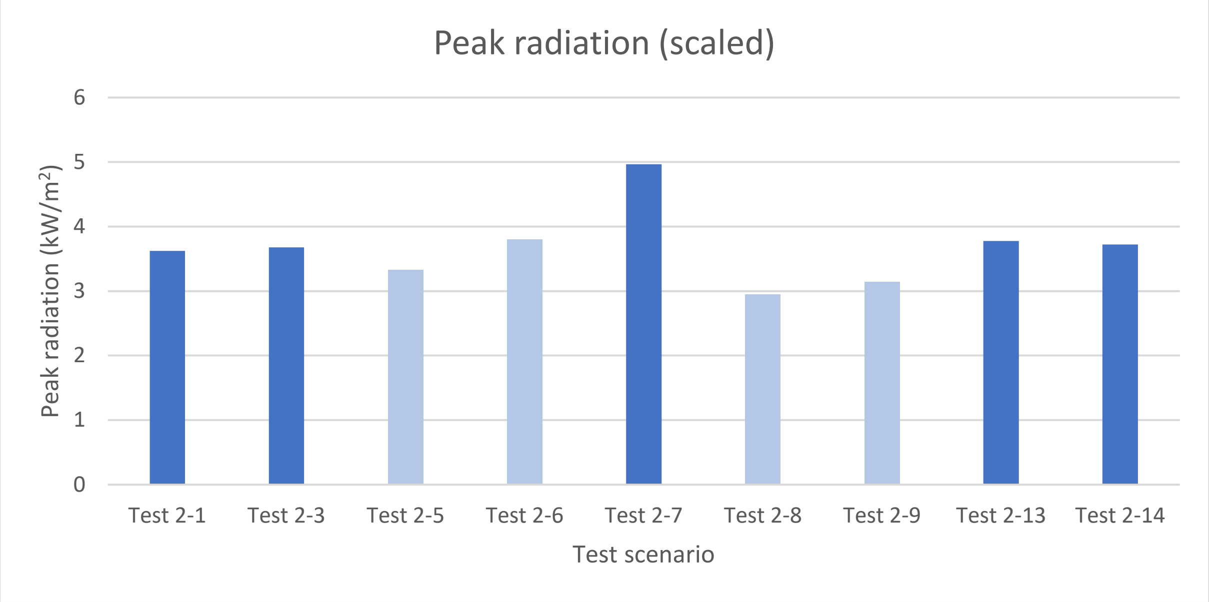


Figure 75: Peak radiation for test scenarios. Columns in darker blue marks the tests where the fire is located in between the supply and exhaust fans (Section 6). Columns in lighter blue marks the tests where the fire is located closer to the exhaust fans (Section 9/10).

All peak radiation values exceed 2.5 kW/m^2. Test 2-7 has the highest peak radiation, almost reaching 5 kW/m^2. Test 2-8 has the lowest peak radiation, below 3 kW/m^2.

9.2.5 Conclusion from model scale test with mechanical ventilation

Main author of the chapter: Stina Andersson, Anna Olofsson, Haukur Ingason, RISE

The light transmission results support the conclusion that fans reduce the amount of smoke inside the space. This in turn indicates that the visibility inside the space improves when fans are used.

The lowest radiation is achieved when fans are shut off. If fans are active, the lowest radiation is achieved when the fire is located close to the exhaust fans. The highest radiation levels are seen if the fans are used when the fire is located “centreline”, i.e., similar distance to the exhaust fan as to the supply fan.

The steel temperature above the fire is higher for the scenario where the fire is located closer to the exhaust fan compared to “centreline”, i.e., similar distance to the exhaust fan as to the supply fan.

9.3 Ship integration and cost assessment

Main author of the chapter: Obrad Kuzmanovic, FLOW

During the project, two solutions were presented in this action. One was a tactical guideline to assist the crew and the second was a SOLAS requirement of reversible fans. These solutions were evaluated from ship integration and cost perspective. Ship integration and cost assessment for reversible fans and tactical guideline are provided here.

9.3.1 Operational, design and construction aspects

As the ventilation system is, in most cases, specially customized for each ship, it is very difficult to issue general guidelines how to operate it during fire incidents. Therefore, standard procedure for most of the operators nowadays is to turn off the fans and close the dampers for avoiding the supply of oxygen and preventing the spreading of smoke. However, in such cases, the conditions are extremely difficult for firefighting team due to low visibility and fire time is extended with clear risk of fire spreading on other vehicles. Thus, the formulation of guidelines would relate to the ventilation operation during small fires, enabling better visibility and conditions to the first response firefighting team and enhancing the odds that the fire can be extinguished fast. Such guidelines, with instructions when to start or shut down the forced ventilation system, which fans may be started, could be very useful from operational and design aspects. Requirement for the equipment within ducts (fans and related cabling) need clearly presented.

The installation of reversible fans shall be recommended for closed ro-ro spaces and their usage will be restricted for smaller fires only (restricted to one vehicle fire). Design wise, reversible fans are well known and widely used on board ships. Further, the ducts and other relevant equipment should be resistant to fire and ventilation outlets should be conveniently located that exhausted gases and smoke do not spread into accommodation, assembly stations nor disrupt working of crew. Such implementation will most probably increase the overall cost of the ship, but the probability for a quick suppression of small fire could be increased. Operationally, the crew must be familiarized and trained with usage of reversible fans and fire procedures.

9.3.2 Cost assessment

According to available information on the ventilation arrangements at ro-ro and ro-pax ships it may be concluded that no additional cost shall be considered by integration of reversible fans, due to typical installation of fans in all ventilation ducts. At the ro-ro cargo generic ship, the ventilation arrangement slightly differs from the typical arrangement and therefore a conservative approach needs to be considered.

The guideline for how to use mechanical ventilation in case of a fire in a closed ro-ro space was part of a full cost-effectiveness assessment and not deemed to be cost-effective since the risk reduction did not balance the cost of implementing the guideline, this is further described in [40].

9.4 Summary regarding mechanical ventilation

From the simulations it can be concluded that reversible fans were beneficial, compared to normally operated fans, i.e., having the chance to reverse the fan and extract gases is positive. The simulation results indicate that mechanical ventilation could facilitate manual firefighting in the early phase of a fire in a closed ro-ro space. When a fire inside a closed ro-ro space exceeds 5 MW (1 car burning), the current praxis of shutting down the ventilation and activate the extinguishing system is not challenged. Visibility of 10 m can be achieved with 16 ACPH when fire located in the proximity of an exhaust fan. It should be noted that the effects on fire spread have not been included in this study.

Regarding visibility for a fire located in the fore part the best conditions are caused with reverse operation of the fans with 16 ACPH. The simulations indicate that a visibility of 10 m can be achieved at a distance of 10 m from the fire source, this is better than 8 and 10 ACPH and also better than having fans off. Within 10 m from the fire source, the visibility decreases below 10 m. For a scenario where the fire is located in the centre part of the ship the best scenario is when the ventilation is on, 8 or 10 ACPH does not make a big difference. The smoke is thinner downstream than upstream of the fire in both cases. The visibility downstream of the fire source is approximately 5-10 m for a reflective sign for both scenario 6 and 7. This is the best result for the visibility and the fire located in the centre part.

With a fire source in the front the temperature at 1.9 m height is generally below 60 °C for the scenarios with the ventilation on. The temperature exceeds the critical value of 60 °C for the scenarios without ventilation after approximately 10 minutes. For the scenarios with reversed ventilation (8 ACPH and 16 ACPH), the temperature is even lower than with normal ventilation. The temperature is generally below 40°C all the way to the fire. This is the lowest result for temperature in scenarios with a fire in the front (scenario 1 to 4). This result indicates that if a fire is located close to a supply fan, it is beneficial to be able to reverse it into an exhaust fan. With a fire in the centreline the temperature exceeds 60°C in most of the ro-ro space after 10 min when the ventilation is off. This is similar to the results for a fire in the front and no ventilation.

The incident radiative heat flux is below the threshold of 2.5 kW/m^2 at 4 m from the fire source from all directions for every scenario (1 to 7). The radiation level is rapidly decreasing with a greater distance to the fire source.

Reversible fans were also studied in model scale tests. The light transmission results in the tests support the conclusion that fans reduce the amount of smoke inside the space. This in turn indicates that the visibility inside the space improves when fans are used.

The lowest radiation was achieved when fans were shut off. If fans were active, the lowest radiation was achieved when the fire is located close to the exhaust fans. The highest radiation levels were seen if the fans are used when the fire is located “centreline”, i.e., similar distance to the exhaust fan as to the supply fan.

The steel temperature above the fire was higher for the scenario where the fire is located closer to the exhaust fan compared to further away and located in the middle of the longitudinal centreline, i.e., similar distance to the exhaust fan as to the supply fan.

10 Development of a guideline

Main authors of the chapter: Stina Andersson, RISE

As part of the work in LASH FIRE, a guideline for how to use mechanical ventilation in case of a fire in a closed ro-ro space was developed. The guideline was developed based on the result and conclusions of the studies carried out and presented within this report. The guideline is a compilation of the most important information and conclusions from the different studies.

To evaluate the guideline, it was sent out to a representative from a ro-pax ship operator, and to three ro-pax crew members. The guideline was updated and adjusted based on their feedback in an iterative process. The first public version of the guideline is presented in ANNEX A - Guideline: Mechanical ventilation in case of fire in closed ro-ro spaces. A final version will be presented at lashfire.eu (website).

The developed guideline was listed as one of the 16 risk control options that was part of a cost-effectiveness assessment where the cost of implementing the guideline was compared to how much the guideline would reduce the fire risk onboard. The guideline was not deemed to be cost-effective since the risk reduction did not balance the cost of implementing the guideline [40]. However, rather than providing direct instructions, the guideline was developed with the aim to increase crew members understanding of both opportunities and risks of using mechanical ventilation during a fire inside a closed ro-ro space. It is meant to constitute a knowledge asset to be explored before a fire occurs. The guideline has a focus on the early phase of the fire scenario, with no fire development and no drencher activation included.

11 Conclusion

Main author of the chapter: Anna Olofsson, RISE

The presented work has determined effects of natural and mechanical ventilation on fire scenarios in ro-ro spaces and evaluated current possibilities and new measures for smoke containment. For natural ventilation, the configuration of openings was evaluated to further understand the effect on the fire development. For mechanical ventilation, the usage of reversible fans as a tool to facilitate manual firefighting was evaluated and validated and led to development of a guideline.

The results in this report contribute to the LASH FIRE objective 1 to strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current and future challenges in different stages of a fire.

Using field studies, computer simulations, model scale tests and interaction with ship operator and crew has been part in the work towards a guideline for understanding natural ventilation affecting fire development and the usage of mechanical ventilation in case of a fire in a ro-ro space. The guideline is presented in ANNEX A - Guideline: Mechanical ventilation in case of fire in closed ro-ro spaces.

- Changed configuration of side openings:

The work was not able to show that the sides openings could be reduced below 10% and still maintain the same air exchange rate as 10 ACPH in a closed ro-ro space. This indicates that, if the opening percentage is to be reduced, mechanical ventilation would be needed to achieve the required air exchange rate. Therefore, a reduced opening percentage in open ro-ro spaces is not deemed to be a feasible way forward without further investigations on air quality.

The conducted simulations and tests regarding natural ventilation shows that closing the permanent side openings affects the fire development and results in a less intense fire, i.e. a lower heat release rate (HRR). It also showed that having one short end open, and side openings closed, is enough to provide a single car fire with enough oxygen to not become ventilation controlled. Changing opening configuration from a generic configuration with openings in the middle of the side plating to openings almost down to the deck while keeping the opening percentage to 10% will not reduce the fire development inside an open ro-ro space.

- Requirement of reversible fans:

Reversible fans are beneficial for having a possibility to change air flow direction depending on the fire location. If a fire is located close to an exhaust outlet, then keeping the fans on at increased capacity decreases smoke density in the space compared to if a fire located in between a supply and exhaust, i.e., having the chance to reverse the fan is positive if it results in a fire located closer to the exhaust (than before the reversing) and extraction of gases. Visibility of 10 m can be achieved with 16 ACPH when fire is located in the proximity of an exhaust fan. The results indicate that mechanical ventilation could facilitate manual firefighting in the early phase of a fire in a closed ro-ro space. When a fire inside a closed ro-ro space exceeds 5 MW (1 car burning), the current praxis of shutting down the ventilation and activate the extinguishing system is not challenged.

- Development of guideline:

For the guideline, only fires in the early stage were included in the study. Keeping the fans on, instead of shutting them off (as of today) and increasing the capacity to at least 16 ACPH resulted in less smoke in the ro-ro space and hence better conditions for manual firefighting due to increased visibility. The fire location should be close to an exhaust fan to be able to use the benefit of this. The study has not included fire spread or drencher activation. Switching fans off is the best alternative to reduce the fire intensity but generates worse visibility conditions.

Using ventilation in case of fire shall be considered with care, without training and understanding it can also cause more harm and other problems to solve. First of all, the guideline is a knowledge asset aimed at improving the understanding of both opportunities and risks with mechanical ventilation during a fire. It is up to each ship to familiarize with the guidelines and to practise and understand how and if mechanical ventilation in case of fire can be a tool on board their vessel. Each fire scenario is unique, and each ro-ro space ventilation set-up and design is unique. The combination of these variables makes it hard to give pre-defined scenarios on which fans to use when in the case of a fire in the ro-ro space.

The developed guideline can be seen as a first step of awareness for keeping fans on in case of fire. Since both a fire scenario and the prevailing conditions are dynamic the study has not been able to cover all scenarios and conditions. More studies can help to reach into more details on different scenarios than has been studied in this work, for example looking into how, if and when to use mechanical ventilation for smoke extraction in the late stage of a fire or when fire is extinguished. But also to further support the crew with training, tools, and scenarios for active usage of fans during a fire.

12 References

[1] A. Olofsson, P. Mindykowski, L. Jiang, A. Rakovic, F. Evegren and H. Ingason, "Model scale tests of a ro-ro space fire ventilation," RISE Researh Institutes of Sweden, RISE Report 2019:94, 2019.

[2] S. Svensson, ”Fire ventilation,” Swedish Civil Contingencies Agency (MSB), 2020.

[3] IMO, *Part 1 DESIGN GUIDELINES FOR VENTILATION SYSTEMS IN RO-RO CARGO SPACES,* London: International Maritime Organization, 2015.

[4] J. Gehandler och H. Ingason, ”Principer och strategier för ventilation vid brand i undermarksanläggningar,” RISE Research Institutes of Sweden, Borås, 2018.

[5] Svensk Ventilation, ”Behovsstyrning ger bättre ekonomi,” Svensk Ventilation, [Online]. Available: https://www.svenskventilation.se/ventilation/behovsstyrning/.

[6] T. Hakkarainen, N. Verma, A. Viitanen och A. Temple, ”Description of development and assessment of safe ro-ro space openings,” LASH FIRE, 2022.

[7] A. Temple, ”Hull Exposure Levels Above Openings and Limits for Unprotected Areas,” LASH FIRE, 2023.

[8] A. Lönnermark och H. Ingason, ”Recent Achievements Regarding Heat Release and Temperatures during Fires in Tunnels,” SP Swedish National Testing and Research Institute, Borås, n.d..

[9] M. K. Cheong, M. Spearpoint och F. Charles, ”Design Fires for Vehicles in Road Tunnels,” i *Proc. 7th International Conference on Performance-Based Codes and Fire Safety Design Method*, Auckland, 2008.

[10] IMO, ”Review of SOLAS Chapter II2 and associated codes to minimize the incidence and consequences of fires on ro-ro spaces and special categpry spaces of new and existing ro-ro passenger ships, Proposal for improving the fire safety of ro-ro spaces and special,” Submitted by China, 2018.

[11] J. e. a. Leroux, *FIRESAFE II Detection and Decision, Final Report, Version 1.1, 2017/EMSA/OP/17/2017,* EMSA, 2018.

[12] IMO, *MSC.1/Circ.1615: Interim guidelines for minimizing the incidence and consequences of fires inro-ro spaces and special category spaces of new and existing ro-ro passenger ships,* London: International Maritime Organization, 2019.

[13] US Coast Guard, ”Code of Federal Regulations (CFR) 46, online edition.,” USCG, 2019.

[14] K. McGrattan, S. Hostikka, J. Floyd, R. McDermott och M. Vanella, ”Fire Dynamics Simulator, User’s Guide (NIST Special Publication 1019),” National Institute of Standards and Technology, 2020.

[15] A. Olofsson, F. Evegren, P. Mindykowski, L. Jiang, K. Ukaj, A. Zawadowska och H. Ingason, ”RO5 ro-ro space fire ventilation Summary report RISE Report 2020:06,” RISE, Borås, 2020.

[16] P. Mindykowski, S. R. Hjohlman Maria, B. Vicard och J. Leroux, ”D11.1 Development, theoretical evaluation and preliminary assessment of requirements for horizontal division of ro-ro spaces,” LASH FIRE, Borås, 2022.

[17] IMO, ”MSC.1/Circ.1002 Guidelines on altrnative design and arrangements for fire safety. Circular issued by IMO following meetings of the Maritime Safety Committee, as amended in 2016.,” IMO, 2016.

[18] Boverket, ”The Swedish National Board of Housing, Building and Planning’s general recommendations on the analytical design of a building’s fire protection, BBRAD.,” 2013.

[19] M. Runefors, ”Zonindelning vid räddningsinsatser mot fordon med alternativa bränslen - beräkningsunderlag,” P. 11-13. Retrieved from https://www.msb.se/sv/publikationer/zonindelning-vid-raddningsinsatser---berakningsunderlag/, 2020.

[20] J. Burgén, J. Gehandler, A. Olofsson, C. Huang och A. Temple, ”Safe and Suitable Firefighting,” RISE, Borås, 2022.

[21] European Committee for Standardization, ”Eurocode 3: Design of steel structures. Part 1-2: General rules. Structural fire design. (EN Standard EN 1993-1-2:2005),” 2005.

[22] W. Zhang, J. Harff och R. Schneider, ”Analysis of 50-year wind data of the southern Baltic Sea for modelling coastal morphological evolution – a case study from the Darss-Zingst Peninsula,” *Oceanologia,* vol. 53, nr 1, Elsevier Urban & Partner Sp. z o.o , SOPOT, pp. 489-518, doi: 10.5697/oc.53-1-TI.489, 2011.

[23] A. Pena Diaz och e. al., ”South Baltic Wind Atlas,” South Baltic Offshore Wind Energy Regions Project, 2011.

[24] M. Rahimpour och P. Oshkai, ”Experimental investigation of airflow over the helicopter platform of a polar icebreaker,” *Ocean engineering, Elsevier Ltd, OXFORD,* vol. 121, pp. 98-111., 2016, doi: 10.1016/j.oceaneng.2016.05.023.

[25] LASH FIRE, ”D09.2 Developed ro-ro spaces fire detection solutions and recommendations,” 2022.

[26] H. Ingason, A. L. A. Berqvist, H. Frantzich och K. Hasselrot, ”Räddningsinsatser i vägtunnlar p. 27-29,” Räddningsverket, Karlstad, 2005.

[27] L. Vylund, J. Gehandler, P. Karlsson, K. Peraic, C. Huang och F. Evegren, ”Fire-fighting of alternative fuel vehicles in ro-ro spaces p. 3,” RISE, Borås, 2019.

[28] Y. Z. Li och T. Hertzberg, ”Scaling of internal wall temperatures in enclosure fires,” SP Technical Research Institute of Sweden, Borås, 2013.

[29] I. Larsson, H. Ingason och M. Arvidson, ”Model Scale Fire Tests on a Vehicle Deck on Board a Ship,” SP Swedish National Testing and Research Institute, SP Report 2002:05, 2002.

[30] J. Sjöström, F. Amon, G. Appel och H. Persson, ”Thermal exposure from large scale ethanol fuel pool fires,” *Fire Safety Journal,* vol. 78, pp. 229-237, 2015.

[31] Schlichting, Hermann (translated by J. Kerstin), ”Boundary-Layer Theory,” McGraw-Hill, New York, 1979.

[32] L. Lewandowski, E. De Carvalho och A. Cassez, ”D04.05 – Development of holistic risk model report,” 2022.

[33] C. Huggett, ”Estimation of rate of heat release by means of oxygen consumption measurements,” *Fire and Materials,* vol. 4, nr 2, pp. 61-65, 1980.

[34] B. Karlsson och . J. G. Quintiere, Enclosure FIre Dynamics, CRC Press LLC, 1999.

[35] M. Hurley, SFPE Handbook of Fire Protection Engineering, 5th edition, Springer, 2016.

[36] Directorate-General for Rail and Marine Investigations, 3rd Division – Marine Investigations, ” Fire on Board Ro-Ro Pax SORRENTO 28 April 2015 - Final Report,” Ministry of Infrastructure and Transport, 2015.

[37] Y. Yao, Y. Z. Li, H. Ingason och X. Cheng, ”Scale effect of mass loss rates for pool fires in an open environment and in tunnels with wind,” *Fire Safety Journal,* vol. 105, pp. 41-50, 2019.

[38] Submitted by Japan, *SSE 5/7 Fire safety measures for ro-ro spaces and special category spaces of new and existing ro-ro passenger ships,* IMO, 2017.

[39] A. Lönnermark och H. Ingason, ”Recent Achievements Regarding Heat Release and Temperatures during Fires in Tunnels,” SP Swedish National Testing and Research Institute, Borås, n.d..

[40] E. De Carvalho och L. Lewandowski, ”D04.6 Cost-effectiveness assessment report,” LASH FIRE, 2023.

13 Indexes

13.1 Index of tables

13.2 Index of figures

14 ANNEX A - Guideline: Mechanical ventilation in case of fire in closed ro-ro spaces

LASH FIRE

LEGISLATIVE ASSESSMENT FOR SAFETY HAZARDS OF FIRE AND INNOVATIONS IN RO-RO SHIP ENVIRONMENT

LASH FIRE
Information
sheet

Mechanical ventilation in case of fire in closed ro-ro spaces (May 2023)

To use mechanical ventilation during a fire in a closed ro-ro space, it is important to be aware of both the opportunities and risks.

Ventilation is of great importance for the fire growth rate, intensity and fire duration in ro-ro spaces. This guideline aims at giving the person responsible for manual firefighting tactics an understanding for how mechanical ventilation can be used during the early phase of a fire event.

The guideline is based on different types of studies. Computation fluid dynamic (CFD) study, model scale testing, in-situ visits, survey and interviews with personnel working with fire safety on board ships. The guideline is relevant for closed ro-ro spaces on board ro-ro passenger ships and ro-ro cargo ships.

Mechanical ventilation can be used to change the conditions in a space so that heat or fire gases flow in a desired direction. Fans are already used by professional firefighting in land-based operations. The usage of mechanical fire ventilation is an active tool, which needs to be adjusted to and during the specific fire scenario.

IMPORTANT FACTORS TO CONSIDER

Before considering using mechanical ventilation during a fire scenario, consider these factors:

Size of fire: This guideline is valid for fires up 5 MW (equals a single car burning). If the fire exceeds 5 MW, the current praxis of shutting off the ventilation and closing the dampers is not challenged.

Location of fire: The placement of the fire in relation to supply/ exhaust fans will affect how fans can be used.

Surrounding cargo: Take into account the risk of fire spread to adjacent cargo with the usage of ventilation.

Available equipment: Reversible fans and temperature sensors can be helpful for a successful fire ventilation strategy.

Ventilation set-up: Consider if the fan configuration onboard can create the desired airflow in the space.

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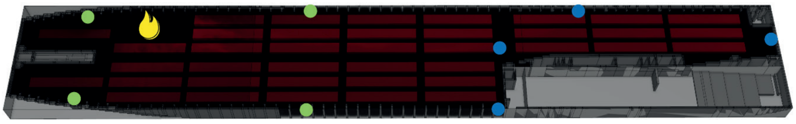
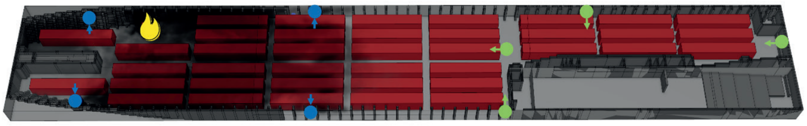
LASH FIRE

Opportunities

Keeping the fans on at increased capacity in the early stages of a fire can reduce the amount of smoke inside a closed ro-ro space. This requires that the fire is less or equal to a single car burning. Computer simulations confirm that the visibility improves when smoke from a burning car close to an exhaust fan is vented away, which would facilitate manual firefighting.

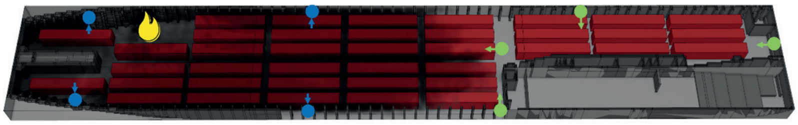


No ventilation (0 ACPH)

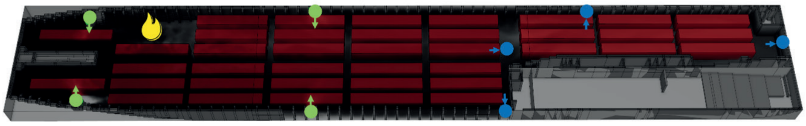


Close to exhaust, increased ventilation (16 ACPH)

Visibility will not improve significantly if fan capacity is not increased or if the fire is located close to supply.



Close to exhaust, fan capacity not increased (8 ACPH)



Close to supply, ordinary capacity (10 ACPH)

● Supply

● Exhaust

Risks

Supply of fresh air through fans can accelerate the fire growth and fire and smoke may spread rapidly throughout the ro-ro space. This may also spread heat and smoke outside the ro-ro space and consequently increase the risk for evacuees in other parts of the ship.

Adaption of guideline and limitations

Since ventilation design is unique for each ro-ro space it is important to make sure that the implementation of this guideline is adapted for the ventilation design and air flow in each ro-ro space. Having knowledge and ship specific practise is a prerequisite for using ventilation in case of fire. Fire spred and drencher activation has not been part in the background studies to this guideline.

VENTILATION STRATEGY

- If the fire exceeds 5 MW (1 single car burning), shut off the ventilation and close dampers.
- If fire is located close to an exhaust, keeping fans active at increased capacity will reduce smoke density.
- If fire is located away from ventilation fans, keeping fans active will thin out smoke downstream, but not enough to facilitate manual fire fighting.
- If fire is located close to a supply fan, keeping fans active will spread the smoke throughout the space.

This ventilation strategy should only be considered if the fire is small (< 5 MW) and manual firefighting is needed. Switching fans off is the best alternative to reduce the fire intensity but generates worse visibility conditions.

When to consider keeping fans on at increased capacity in an early phase of a fire (< 5 MW) in a closed ro-ro space?

Location of fire / Type of intervention	Fire location close to supply fan	Fire location close to exhaust fan
Manual firefighting	NO	YES
Activation of extinguishing system	NO	NO

Disclaimer. *This work was produced as part of LASH FIRE action 11-D. It is a knowledge asset aimed at improving the understanding of both oppurtunities and risks with mechancial ventilation during a fire. It is published in the deliverable D11.5*

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