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Fire-safe distance between ro-ro space openings and life-saving appliances

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Abstract

As part of the FIRESAFE II project commissioned by the European Maritime Safety Agency a study was performed to determine a safe distance between side openings and Life-Saving Appliances (LSA) in ro-ro spaces to keep them available and usable for evacuation. The study utilised analytical calculations and CFD simulations. Two exclusion zones, where LSA should not be placed, were defined. The first zone relates to LSA within an embarkation station and includes the full vertical side of the ship, 6 metres forward and aft the opening. The second zone, without presence of passengers, consisted of the exclusion zone extending 6 metres around the opening.
The results presented in the paper have been implemented in the International Maritime Organization interim guidelines for minimising the incidence and consequence of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships.

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1. Introduction

To allow safe abandonment of a ship in case of fire, the Life-Saving Appliances (LSA) onboard must stay available and usable. Ships, especially those with ro-ro spaces, often have permanent side openings and end openings which can endanger the safe usage of the LSA in case of a fire in the ro-ro space.

SOLAS regulation II-2/20.3.1.5 provides a requirement stating that "permanent openings in the side plating, the ends or deckhead of the space shall be so situated that a fire in the cargo space does not endanger stowage areas and embarkation stations for survival craft [1]".

However, this regulation is open to interpretations as neither detailed requirements nor guidelines are available to ensure that the requirements are met. There is also no literature defining a safe distance between openings and LSA.

In order to determine a safe distance (which keeps any LSA available and usable), an investigation was conducted by Bureau Veritas Marine & Offshore, RISE Research Institutes of Sweden, and Stena Rederi as part of the project FIRESAFE II, commissioned by the European Maritime Safety Agency. This project has focused on different aspects of safety onboard as Detection and Decision [2], Containment and Evacuation [3], new means of fire detection [4], and new means of fire extinguishing systems [5].

Computational Fluid Dynamics simulations were used to evaluate the incident radiant heat flux from flames exiting ro-ro space side openings, and analytical calculations were used to evaluate openings aft of a ship. Consideration was given to the fire integrity of LSA and the impact of smoke.

2. Methods

2.1. Safety Distance for Exposure to Radiant Heat Flux

In order to evaluate a safety distance with respect to radiant heat flux exposure, criteria on fire integrity have been developed.

A. Criteria for exposure to radiant heat flux

Any LSA must be protected from the fire such that it is not damaged by any fire (e.g., via melting or deformation of the LSA leading to them being unusable). In addition, some LSA, such as lifeboats, must also be provided with protection for passengers who are utilizing them. Any criteria utilized to define a safety distance must take these into account.

The initial consideration was given to the fire resistance requirements for LSA [6]. However, these were considered not to be suitable. These fire safety requirements are based on a material test where a sample is exposed to an incident radiant heat flux of 50kW/m2. The pass-fail criteria for this test are based on the time to ignition, namely that the material should not ignite within the first 40 seconds of the test, as detailed in MSC/Circ.1006 [7]. The results of this test will indicate the reaction to a material's fire properties, and any material that does not pass should not be utilized for LSA. However, it does not indicate the risk of the LSA's melting and deformation, which could render it unusable at lower heat fluxes. It was, therefore, necessary to establish a set of new criteria that are applicable for critical heat exposure at a larger distance in this study.

At a fundamental level, materials exposed to radiant heat will ignite when the radiant heat flux exceeds a critical value [8]. The critical heat flux is defined as either the minimum radiant heat flux required to ignite a material or the maximum radiant heat flux, which will not cause ignition during a period of 60 minutes. The SFPE Handbook of Fire Protection Engineering lists typical materials and their critical radiant heat flux. Table 1 shows an extract for a group of materials used for LSA. In order to keep LSA available and usable, a conservative decision was made to determine a criterion regarding the maximum radiant heat flux of 5.0 kW/m2. The chosen criterion was based on the low value in the range of critical heat fluxes for the materials presented in Table 1, 10 kW/m2, divided by a safety factor of 2.

Table 1. Some materials used in LSA and their critical heat fluxes for ignition [8]

Material	Critical Heat Flux (kW/m^2)
Synthetic materials	10 - 16
Halogenated materials	10 - 50
Composite and Fiberglass-Reinforced materials	10 - 40
Foams (Wall ceiling insulation materials, etc.)	10 - 40
Materials with Fiberweb, Net-Like and multiplex structures	8 - 18

It should be noted that some LSA is not only stowed and then directly released into the water, but some also include an embarkation station for the passenger. A parametric study was performed to determine safety distances between openings and LSA for the incident radiant heat flux from flames exiting the opening. The incident radiant heat flux depends on the flame emissive power (itself dependent upon the fuel type, flame shape, etc.) and the distance between the flame and the target. The critical incident radiant heat flux corresponds to the criteria discussed earlier in Table 2. Numerical simulations were performed to determine the flame emissive power, as described below, and then to determine safety distances (e.g., lifeboats). For such LSA, the previous criterion cannot be used. A radiant heat flux higher than 2.5 kW/m2 is critical and harmful for persons without thermal protection [8] and is a life-safety criterion stated in MSC.1/Circ.1552 [9] (amendment to MSC/Circ.1002 [10]). Hence, two criteria based on radiant heat flux exposure were proposed, as presented in Table 2.

Table 2. Proposed radiant heat flux safety criteria for LSA

Type of LSA*	Maximum incident radiant heat flux allowed at the LSA (kW/m^2)
Presence of passengers (Lifeboat, launching appliances, embarkation stations, MES)	2.5
No passengers (Life raft)	5.0

*In the present study, only survival craft type LSA were considered.

A parametric study was performed to determine safety distances between openings and LSA for the incident radiant heat flux from flames exiting the opening. The incident radiant heat flux depends on the flame emissive power (itself dependent upon the fuel type, flame shape, etc.) and the distance between the flame and the target. The critical incident radiant heat flux corresponds to the criteria discussed earlier in Table 2. Numerical simulations were performed to determine the flame emissive power, as described below, and finally, determine safety distances.

3. Results and Discussion

3.1. Radiant Heat Flux From End Openings or Weather Deck: Analytical Calculations

LSA located adjacent to, above, and/or forward of the weather deck could be exposed by a fire on the weather deck itself. Or to a fire within the ro-ro space via the large openings common in transitioning from a ro-ro space onto a weather deck. In order to estimate the radiant heat flux to which LSA could be exposed, analytical calculations were conducted. The analytical approach was based on the solid flame radiation model, which approximates the flame as a solid rectangular emitter. The geometry of the rectangle (base and height) and its equivalent flame emissive power were based on the typical cargo (i.e., fuel giving mass burning rate and effective heat of combustion) in a ro-ro space (fuel area). A short explanation of the solid flame model is given below, while further details of this model are available in the SFPE Handbook, chapter 2 [8]. For the example case, the fire was assumed to be represented by three half cargo units burning side by side. The incident radiant heat flux towards a target is a function of the emissive power of the flame and the view factor between the flame and the LSA, as described by Eq. (1).

$$Q_{inc} = E \times F_{flame \to target} \tag{1}$$

The main approximation of this model is that the flames from a solid material fire, like burning cargo units, are equivalent to a liquid pool fire. This approximation thus allows the calculation of an equivalent fire diameter for the cargo units to use within pool fire relationships. This equivalent diameter is defined in **Error! Reference source not found.** [11].The average emissive power of the flame can then be determined for solid materials using Eq. (2) [12].

$$E = 58 \times (10^{-0.00823 \times D}) \tag{2}$$

$$D = HRR/(4 \times 320 \times H_{cargo}) \tag{3}$$

For Eq. (1). it is also necessary to define of the view factor between the flame and the target. This view factor is given by Eq. (4)

$$F_{flame \to target} = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}} arctan\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}} arctan\left(\frac{X}{\sqrt{1+Y^2}}\right)\right] \tag{4}$$

where $X = \frac{H_{visible\ flame}}{distance\ flame-target}$; $and\ Y = \frac{width\ of\ the\ fire\ wall}{distance\ flame-target}$

An unknown parameter in this equation is the flame height, which is deduced from Eq. (5) and Eq. (6) [13]:

$$H_f = 0.235 \times HRR^{\frac{2}{5}} - 1.02 \times D \tag{5}$$

Where, HRR is the heat release rate from the fire and is defined as:

$$HRR = \dot{m}'' \times \Delta H_c \times A \tag{6}$$

In the example case, the fire area was estimated to be 112 m2 (external areas of three half cargo units), giving an equivalent 9.1 m diameter as defined by Equation 3. The considered scenario was a fire of cargo units situated in the worst position, on the edge between the weather deck and a closed ro-ro space (so-called garage). In 1997 Arvidson [14] estimated the typical cargo of a "freight truck". Unfortunately, the multi-material nature of this data means it is not suitable for direct use in a solid flame model. The overall data from Arvidson was converted into an equivalent material with an average combustion and burning rate heat, as presented in Table 3. Based on the data from Table 3 and Eq. (6), the heat release rate of the cargo fire was calculated to be 35 MW. With a height of about 6.2 meters and a flame emissive power of 48.79 kW/m2, as per Eq. (5) and Eq. (2), respectively.

Table 3. Thermo-physical data used as input for the solid flame model [14]

Item	Weight (kg)	Heat of combustion (MJ/kg)	Mass burning rate (g/m^2s)
Polystyrene cups	1 620	27	36
Cardboard boxes	4 032	15.6	26
Tarpaulin	984	20.6	14
Tailgates	852	14	6
Equivalent material	7 488	19.95	15.61

The height of the flame visible to the LSA was calculated to be 4.8 meters. The safety distances can be determined using the criteria given in Table 2 using Eq. (1). and Eq. (4). From these results the safety distances between the edge of the flame (edge of the top deck) and LSA were determined, as summarized in Table 4. It should be noted that these analytical calculations are dependent on the geometry of the ro-ro space (receiving the cargo and where the LSA are situated). For the cases where the height of the deck matches the 5.5 m utilized in the example case, the safety distances presented in Table 4 can be used.

Table 4. Safety distances for LSA on the top deck of the ship

Type of LSA	Maximum radiant heat flux allowed at the LSA (kW m^{-2})	Safety distance
Presence of passengers (Lifeboat, embarkation stations and MES)	2.5	13 m
No passengers (Life raft stowage areas)	5.0	8 m

3.2. Radiant Heat Flux From Side Openings: Numerical Simulations

To find the shape and thermal characteristics of flames exiting side openings of an open ro-ro space, numerical simulations were performed with Fire Dynamics Simulator software [15] FDS is a computational fluid dynamics (CFD) model of fire-driven flow and solves numerically a form of the Navier-Stokes equations appropriate for low-speed ($Ma < 0.3$), thermally driven flow with an emphasis on smoke and heat transport from fire. A generic ro-ro space was used as the basis for these simulations.

Some of the simulation parameters used were:

- Cell size: 20cm x 20 cm x 20cm for the flaming zone, and 40 cm x 40 cm x 40 cm elsewhere
- Soot yield: 0.06 g/g
- Carbon monoxide yield: 0.1 g/g
- Materials for the ceiling and floor: unprotected steel
- A-class division bulkhead
- Ro-ro space load configuration: fully loaded with cars and trucks
- Ro-ro space was naturally ventilated (i.e. no mechanical ventilation system)

In order to maximize the heat exposure to any LSA, a fast fire growth rate was used with a fire duration of 20 minutes to ensure that a fully developed fire was reached. Additionally, high wind velocities were used in the simulation to maximize the heat exposure in the downwind direction. Table 5 presents the different peak heat release rates, wind velocities, and the wind directions used in the simulations.

Table 5. Input values used in the fire scenarios simulated to evaluate radiative heat flux through ro-ro space side openings

Total Heat Release Rate (MW)	Exterior Wind velocity in the x axis (m s^{-1})	Exterior Wind velocity in the y axis (m s^{-1})
2, 6, 10, 25, 50	2, 5, 7	2, 5, 7

One advantage of using numerical simulations is that the output directly provides the incident radiant heat flux at specified locations using virtual sensors. The scenario with the highest heat release rate and wind velocity naturally resulted in the highest radiant heat flux close to the openings. Based on the simulation results, it was possible to determine zones around openings on the ship where LSA should be excluded. For LSA without the presence of passengers (e.g., life rafts launched directly into the water), the exclusion zone (exclusion zone 1) extends to 6 meters around the opening. For LSA with the presence of passengers (e.g., lifeboats for embarking passengers), the exclusion zone (exclusion zone 2) includes the full vertical side of the ship, 6 m forward and aft of the (width of the) opening. These exclusion zones are illustrated in Fig. 1 and are, below, collectively referred to as "critical zones" concerning openings and evacuation safety.

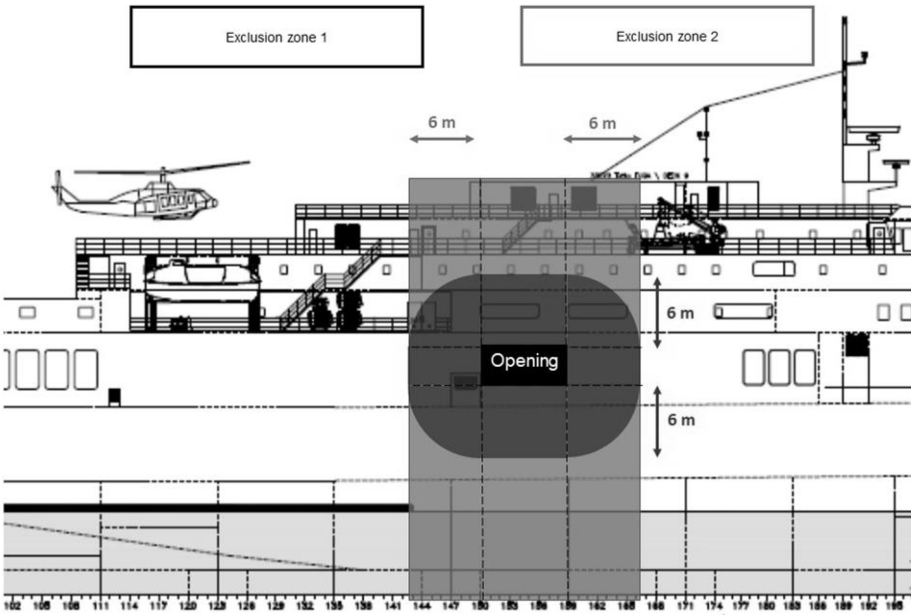

Figure 1. Zones in which LSA should be excluded, where exclusion zone 1 applies to LSA which may involve passengers and exclusion zone 2 applies to LSA which do not involve passengers (e.g. life rafts launched directly into the water).

3.3. Safety Distance in Case of Smoke Exposure

To determine a safety distance between openings and LSA with respect to smoke exposure, analytical calculations were carried out. As a first approximation, the smoke plume from an opening can be approximated as a plume coming from a chimney, ignoring any influence from wind. When the safety target is near the source (example case), the radius (R) of the plume is dominated by its momentum (buoyancy effect) and then only dependent of its elevation (z) [16], in accordance with Eq. (7).

$$R(z) = R(z_0) + \Delta R(z) = R(z_0) + (0.16 \times z) \tag{7}$$

As the plume radius increases with height, the worst-case scenario (i.e. the maximum elevation of the plume interacting with any LSA) is the maximum height from any openings to the LSA on the considered ship. This maximum elevation was measured based on the general arrangement drawings of different types of ro-ro passenger ships (3 types have been selected during the study) and is presented in Table 6.

Table 6. Maximum variation of the plume radius for different types of ro-ro passenger ships

Type of RoPax	Maximum elevation (m)	Maximum variation of the smoke plume radius (m)
Standard RoPax	15	2.4
Cargo RoPax	16.96	2.7
Ferry RoPax	23.6	3.7

Since smoke and its content of toxic gases are harmful to passengers, as a criterion, it was assumed that LSA should not be allowed within the smoke plume. Using a safety factor of 2 with the plume radius, the exclusion zone for smoke exposure (Exclusion zone 3) includes an area extending from the bottom and 3.8 m forward and aft of the opening. However, as this exclusion zone is within exclusion zone 2, no additional considerations or limitations are required concerning it. It should be noted that smoke may spread with the wind and cause unsafe conditions beyond the critical zones (exclusion zones 1, 2, and 3). However, within the critical zones, smoke or flame spread was always assumed to cause unsafe conditions for evacuation. For example, in an unfortunate scenario, wind conditions could affect evacuation safety outside the critical zone. The safety distance between openings and LSA, considering exposure to radiant heat and smoke as well as different types of LSA (involving passengers or not), are presented in Table 7.

Table 7. Required safety distances from ro-ro space side openings to LSA

Opening	Exposure	Type of LSA	Safety distance from opening (m)
Side opening	Radiant heat flux	With passengers	Horizontal: 6 m Vertical: Height of the ship
	Radiant heat flux	Not with passengers	6 m
	Smoke	All types	Horizontal: 6 m Vertical: Height of the ship
Aft opening	Radiant heat flux	With passengers	13 m
	Radiant heat flux	Not with passengers	8 m

4. Conclusion

As part of the project FIRESAFE II, conducted by Bureau Veritas Marine & Offshore, RISE Research Institutes of Sweden, and Stena Rederi and commissioned by the European Maritime Safety Agency, an investigation was performed using numerical simulations with Fire Dynamics Simulator (FDS), and analytical calculations to determine safe distances to keep LSA available and usable for different fire scenarios. The numerical simulations were used to estimate the incident radiant heat flux from flames exiting side openings of a ro-ro space (where a fire is developing). The analytical approach was used for a fire in a ro-ro space (near an aft opening) or on a weather deck. Moreover, an analytical study was performed to obtain the safety distance between side openings and LSA regarding the impact of smoke (i.e., where smoke spills from the openings). Two types of pass/fail criteria were defined. The first relates to embarkation stations for passengers. According to MSC.1/Circ.1552 [9], the maximum incident radiant heat flux allowed for life safety is 2.5 kW/m2. For the second, LSA stowage without passenger embarkation, the criterion was set to 5.0 kW/m2 and was based on material ignitability data.

To determine safety distances between openings and LSA, a parametric study was performed. The incident radiant heat flux depends of the flame emissive power (itself dependent on the fuel type, flame size, etc.) and the distance between the fire and the endpoint. Calculations were performed to determine the flame emissive power, and finally to determine zones around openings on a ro-ro passenger ship where LSA need to be excluded to ensure availability and usability.

For stowed LSA without embarking passengers (e.g. life rafts launched directly into the water), the exclusion zone (dark grey exclusion zone 1 in Figure 1) extends to 6 m around the opening. For LSA with the presence of passengers (e.g. lifeboats with embarking passengers), the exclusion zone (light grey exclusion zone 2 in Figure 1) includes the full vertical side of the ship, 6 m forward and aft of the opening.

Finally, it should be noted that the results from this study have been implemented in the interim guidelines for minimizing the incidence and consequence of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships, MSC.1/Circ.1615 [17]. These interim guidelines stipulate in paragraph 5 "Integrity of life-saving appliances and evacuation". For new and existing ships, the following safety distances (measured horizontally) are recommended to avoid jeopardizing life-saving appliances and embarkation stations in case of fire in ro-ro and special category spaces:

- survival craft and marine evacuation systems stowed and in a position to be deployed:
  - more than 6 m from a cargo space side opening; and
  - more than 8 m from cargo on weather deck; and
- survival craft embarkation stations and muster stations located:
  - more than 6 m away from a cargo space side opening; and
  - more than 13 m from cargo on weather deck.

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