Horizon 2020

Project acronym: **LASH FIRE**

Project full title: **Legislative Assessment for Safety Hazard of Fire and Innovations in Ro-ro ship Environment**

Grant Agreement No: **814975**

Coordinator: **RISE Research Institutes of Sweden**

Internal Report IR11.15

Calculation methods for safety distances of ro-ro space openings

February 2023

Dissemination level: **Public**

Abstract

Fires in open ro-ro spaces have been identified as a serious hazard since the generated heat and smoke can spread through ro-ro space openings to critical areas such as embarkation stations and life-saving appliances, thus endangering safe evacuation. Implementing safety distances between ro-ro space openings and these critical areas has been found to be an effective way to ensure the safety of the critical areas. However, the definition of proper safety distances is challenging, requiring further research and validation work. In the future, it might be possible to use either prescriptive values defined in IMO regulations or ship-specific values based on alternative, performance-based design. The alternative approaches for defining suitable safety distances could be either analytical calculation tools or advanced computational methods.

This report describes analytical calculation methods for estimating the incident heat flux emerging from side and end openings in case of a ro-ro space fire. By defining critical heat fluxes, safety distances can be determined.

In the FIRESAFE II project, safety distances for exposure to radiant heat flux were studied by numerical simulations and analytical calculations. The analytical formula used in FIRESAFE II study was used as the basis of further work presented in this report. Modifications and additions were made to produce a more advanced analytical formula. Example calculations with the modified analytical method were performed to illustrate the calculation procedure. Selected scenarios from LASH FIRE Task T11.10 CFD simulations were used as example cases. Finally, the limitations of the proposed analytical calculation method were discussed.

The proposed analytical method covers fires near side openings and end openings. The assumed heat release rate of a vehicle on fire is a key input for the proposed method, and the subsequent calculations primarily involve radiant heat flux, flame height, and velocity in a plume, along with other geometrical and environmental inputs. This method can be applied to different fire sizes to calculate incident radiant heat fluxes and resulting safety distances.

Also another potential method for defining safety distances is introduced in this report. This method utilizes various simulation results to produce a linear relationship between the assumed size of a fire and the resulting safe distance around openings. This method requires only fire size as an input and gives safe distances as an output without intermediate calculations. The results indicate that the safety distances linearly increase with increasing fire size. Thus, a linear regression model can be developed to determine safety distances for different fire sizes.

In addition, a parametric study on the combined effect of different fire sizes with different opening widths was performed to support the selection of an optimum opening size concerning the perceived risk of fire in a critical area. It was demonstrated that the size of the openings has a considerable effect on the radiant heat flux around the openings. Smaller fires with bigger openings can have the same impact as larger fires with smaller openings. A large fire with a relatively small opening size can reduce the impact of fire in the area of interest. On the other hand, a small fire with a rather large opening size can increase the impact of fire in the area of interest. The results can be utilized to reduce the effects of a fire near a critical area by choosing the optimum size for openings that also meet the ventilation requirement of the deck.

It is noted that in the development of the proposed analytical methods only one ship geometry and a limited number of different wind speeds were considered. It has not been investigated to what extent the proposed methods are applicable to ships with different arrangements or to scenarios with different environmental conditions at sea.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814975

Document data

Document Title:	IR11.15 – Calculation methods for safety distances of ro-ro space openings		
Work Package:	WP11 – Containment		
Related Task(s):	T11.10		
Dissemination level:	Public		
Lead beneficiary:	02 – VTT		
Responsible author:	Tuula Hakkarainen		
Co-authors:	Nikhil Verma, Alexandra Viitanen		
Date of delivery:	2022-09-01		
References:	IR11.7, D11.4		
Approved by	Pascal Boulet on 2022-07-20	Pierrick Mindykowski on 2022-07-19	Maria Hjohlman on 2022-08-20

Involved partners

No.	Short name	Full name of Partner	Name and contact info of persons involved
02	VTT	Teknologian tutkimuskeskus VTT Oy	Tuula Hakkarainen, tuula.hakkarainen@vtt.fi

Document history

Version	Date	Prepared by	Description
01	2022-07-11	Nikhil Verma, Alexandra Viitanen, Tuula Hakkarainen	Draft of final report, circulated to reviewers
02	2022-09-01	Tuula Hakkarainen, Nikhil Verma	Final report. Dissemination level: Confidential
03	2023-02-23	Tuula Hakkarainen, Nikhil Verma	Final report. Dissemination level: Public

Contents

1 Executive summary

1.1 Problem definition

The main goal of Action 11-C is to develop design guidelines for ro-ro space openings by assessment of the risks of smoke and heat transfer from ro-ro space openings to life-saving appliances, adjacent areas and ventilation inlets.

Implementing safety distances between ro-ro space openings and these critical areas has been found to be an effective way to ensure the safety of the critical areas. However, the definition of proper safety distances is challenging, requiring further research and validation work. In the future, it might be possible to use either prescriptive values defined in IMO regulations or ship-specific values based on alternative, performance-based design. The alternative approaches for defining suitable safety distances could be either analytical calculation tools or advanced computational methods (such as Computational Fluid Dynamics (CFD) models).

This report, linked with Task T11.10, describes analytical calculation methods for estimating the incident heat flux emerging from side and end openings in case of a ro-ro space fire. By defining critical heat fluxes, safety distances can be determined.

1.2 Technical approach

In the FIRESAFE II project, safety distances for exposure to radiant heat flux were studied by numerical simulations and analytical calculations. The analytical formula used in FIRESAFE II study was used as the basis of further work in LASH FIRE Task T11.10. Modifications and additions were made to produce a more advanced analytical formula. Example calculations with the modified analytical method were performed to illustrate the calculation procedure. Selected scenarios from LASH FIRE Task T11.10 CFD simulations were used as example cases. Finally, the limitations of the proposed analytical calculation method were discussed.

Another potential method for defining safety distances introduces a linear relationship between the assumed size of a fire and the resulting safe distance around openings. This method requires only fire size as an input. The results indicate that the safety distances linearly increase with increasing fire size. Thus, a linear regression model can be developed to determine safety distances for different fire sizes.

In addition, a parametric study on the combined effect of different fire sizes with different opening widths was performed to support the selection of an optimum opening size concerning the perceived risk of fire in a critical area.

1.3 Results and achievements

An analytical calculation method has been formulated to define safety distances around or near ro-ro space openings. With certain limitations, the method can be applied to different fire sizes to calculate incident radiant heat fluxes and resulting safety distances. Another analytical calculation method has been defined, based on linear regression utilizing simulation results. It can be an alternative way to find safe distances against different fire sizes.

A parametric study on the combined effect of different fire sizes with different opening widths indicated that smaller openings reduce the effect of radiation around them. Thus, risk reduction measures can also include the flexibility to dimension the openings in critical areas practically smaller in size, in conjunction with ventilation requirements for the deck having such openings.

1.4 Contribution to LASH FIRE objectives

The objective of WP11 is to eliminate significant containment weaknesses, considering smoke, fire, and heat integrity. This is achieved by four actions (11-A to 11-D). This internal report is related to Action 11-C Safe design with ro-ro space openings. The goal of Action 11-C is to develop design guidelines for ro-ro space openings by assessment of the risks of smoke and heat transfer from ro-ro space openings to life-saving appliances, adjacent areas, and ventilation inlets.

The work in WP11 is related to LASH FIRE *Objective 1*: *LASH FIRE will 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*.

This internal report contributes both to the objective of Action 11-C and the objectives of the LASH FIRE project.

1.5 Exploitation and implementation

The results can be used to revise international IMO regulations and support decision making. The goal is that according to revised IMO regulations it could be possible to use either defined prescriptive values or ship-specific values based on alternative, performance-based design. The analytical calculation methods presented in this report support this development.

End users and shipyards can use the results to support fire-safe design of ships. Safer designs with ro-ro space openings would improve the management of fires on ro-ro ships and increase the overall fire safety of ro-ro ships.

2 List of symbols and abbreviations

Symbols

$\boldsymbol{A}$	Area of fuel
$\boldsymbol{D}$	Equivalent fire diameter
$\boldsymbol{d_{flame-target}}$	Distance between flame and target
$\boldsymbol{d_{shift}}$	Shift in radiation source
$\boldsymbol{e}$	Standard error
$\boldsymbol{E}$	Average flame emissive power
$\boldsymbol{F_{f\to t}}$	View factor
FS	Fire size in MW
$\boldsymbol{\Delta H_c}$	Heat of combustion
$\boldsymbol{H_{cargo}}$	Height of cargo
$\boldsymbol{H_{deck}}$	Height of deck
$\boldsymbol{H_{distance\ to\ deck}}$	Distance to deck (from opening midpoint to upper deck)
$\boldsymbol{H_f}$	Flame height
$\boldsymbol{H_{opening\ midpoint}}$	Height of opening midpoint
$\boldsymbol{H_{visible\ flame}}$	Height of visible flame
$\boldsymbol{HRR}$	Heat release rate
$\boldsymbol{\dot{m}''}$	Mass flux
$\boldsymbol{Q_{inc}}$	Incident radiant heat flux
$\boldsymbol{u_{deck\ edge}(z)}$	Fire plume velocity at deck edge
$\boldsymbol{u_{wind}}$	Velocity of wind
$\boldsymbol{w_{flame}}$	Width of flame
$\boldsymbol{z}$	Vertical distance of interest from opening midpoint
$\boldsymbol{\alpha}$	Plume tilt angle
$\boldsymbol{\kappa}$	McCaffrey plume model constant
$\boldsymbol{\eta}$	McCaffrey plume model constant

Abbreviations

CFD	Computational Fluid Dynamics
HGV	Heavy Goods Vehicle
IMO	International Maritime Organization
LSAs	Life-Saving Appliances

3 Introduction

Main author of the chapter: Nikhil Verma, VTT

3.1 Task definition and role in the project

This internal report IR11.15 is connected to task T11.10 (Establishment of safe design with ro-ro space openings) under Action 11-C of WP11. To meet the objective of WP11 (Containment) to eliminate significant containment weaknesses, considering smoke, fire and heat integrity, Action 11-C focuses on developing ro-ro space opening design guidelines. Guideline development has been done by assessing the risks of smoke and heat transfer from ro-ro space openings to life-saving appliances (LSAs), adjacent areas and ventilation inlets.

Task T11.10 has established a safe design with ro-ro space openings by assessment of fire exposure through ro-ro space side and ventilation openings (including outlets for mechanical ventilation) based on heat transfer and smoke spread simulations. The safe design includes safety distances and arrangement of openings in relation to, e.g., air inlets and endangered areas, in particular LSAs and embarkation stations. Safety criteria based on material data and human critical conditions have also been established.

IR11.15, covering the objective of task T11.10, aims to provide analytical methods to calculate safety distances for ro-ro space openings. Such methods are alternatives to CFD-based simulations. The proposed method involves step-by-step calculations leading to safe distances around ro-ro space openings.

3.2 Background

In the accident onboard Norman Atlantic, a fire in an open ro-ro space spread to the starboard rescue boat through side openings (Ministry of Infrastructure and Transport, 2014). Side openings have been identified as a fire hazard also in the FIRESAFE II project (Leroux et al., 2018). In FIRESAFE II, different methods for reducing the risks due to side openings were studied. Based on the results, closing or prohibiting side openings was not considered cost efficient, but instead safety distances between critical areas and side openings should be implemented for ensuring safe design.

This work aims to further study the safe arrangement of ro-ro space openings in relation to critical areas onboard ro-ro vessels. The regulatory, environmental, operational and shipyard requirements for ro-ro space openings and fire containment have been reviewed and discussed in LASH FIRE internal report IR11.3 (Hakkarainen et al., 2020), and the consolidation of the requirements is presented in LASH FIRE deliverable D11.4 (Hakkarainen et al., 2022). The findings of the report shall be considered both when modifications to the design are proposed and when they are evaluated.

4 Methodology

Main author of the chapter: Nikhil Verma, VTT

In the FIRESAFE II project, safety distances for exposure to radiant heat flux were studied by numerical simulations and analytical calculations (Leroux et al., 2018). The analytical formula used in the FIRESAFE II study was utilized as the basis of further work in LASH FIRE Task T11.10. Modifications and additions were made to produce a more advanced analytical formula. Example calculations with the modified analytical method were performed to illustrate the calculation procedure. Selected scenarios from LASH FIRE Task T11.10 CFD simulations were used as example cases. Finally, the limitations of the proposed analytical calculation method were discussed.

The proposed analytical method covers fires near side openings and end openings. Horizontal distances are calculated. As openings are recommended not to be positioned below Life-Saving Appliances (LSAs), safe vertical distances cover the whole area above the openings where no LSAs are recommended. The assumed heat release rate of a vehicle on fire is a key input for the proposed method, and the subsequent calculations primarily involve radiant heat flux, flame height, and velocity in a plume, along with other geometrical and environmental inputs. For this study, a fire with maximum heat release rate of 85 MW was chosen since it is representative of a heavy goods vehicle (HGV) fire with delayed drencher operation (Cheong et al., 2014).

Annex A presents another potential method which utilizes various simulation results to produce a linear relationship between the assumed size of a fire and the resulting safe distance around openings. This method only requires fire size as an input and gives safe distances as output without intermediate calculations to be done by users. The method is exemplified using the simulation model of Stena Flavia. Results are dependent on assumptions made for simulations like wind speed, soot yield, carbon monoxide yield etc. Any change in assumptions will be reflected in results.

Annex B covers a parametric study on the combined effect of different fire sizes with different opening widths based on simulations. It has been demonstrated that the size of the openings considerably affects radiant heat flux around them. The results can be utilized to reduce the effects of a fire near a critical area by choosing the optimum size for openings that also meets the ventilation requirement of the deck.

5 Analytical calculations based on modified FIRESAFE II method

Main authors of the chapter: Alexandra Viitanen and Nikhil Verma, VTT

In the following subsections, analytical calculation methods are described to estimate the incident heat flux for side openings and end openings. The described methods are based on the modifications proposed on the FIRESAFE II calculation method.

5.1 Fire near a side opening

5.1.1 Procedure parts from FIRESAFE II

The following procedure parts regarding incident radiant heat flux proposed in FIRESAFE II (Leroux et al., 2018) are used:

Calculation of incident radiant heat flux (SFPE, 2002):

$$Q_{inc} = E \cdot F_{f\to t} \tag{1}$$

where Q_{inc} is the incident radiant heat flux, E the average flame emissive power and $F_{f\to t}$ the view factor.

Calculation of average flame emissive power *E* (Beyler & Shokri, 1989):

$$E = 58 \cdot 10^{-0.00823 \cdot D} \tag{2}$$

where *D* is the equivalent fire diameter.

Calculation of view factor $F_{f\to t}$ (SFPE, 2002):

$$F_{f\to t} = \frac{1}{2\pi}\left(\frac{x}{\sqrt{1+x^2}} arctan\left(\frac{y}{\sqrt{1+x^2}}\right) + \frac{y}{\sqrt{1+y^2}} arctan\left(\frac{x}{\sqrt{1+y^2}}\right)\right) \tag{3}$$

where $x = \frac{H_{visible\,flame}}{d_{flame-target}}$ and $y = \frac{w_{flame}}{d_{flame-target}}$. The $d_{flame-target}$ is varied, until the incident radiative heat flux is within acceptable limits.

5.1.2 Modifications and additions proposed to the FIRESAFE II approach

To account for flame height outside the openings, flame height H_f is calculated as Lattimer (2016):

$$H_f = 0.0321 \left(\frac{HRR}{D}\right)^{2/3} \tag{4}$$

where *HRR* is the heat release rate outside the opening. Equivalent diameter *D* is calculated based on the side opening area, i.e., by solving what is the diameter of a circle with an equivalent area.

To find suitable values for *HRR*, the analytical calculations were calibrated based on the simulation results from LASH FIRE T11.10, reported in IR11.7 (Hakkarainen et al., 2021). It was found that when the fire is located near an opening and wind is absent, it can be assumed that 5.25 % of the *HRR* is occurring outside the side opening which is on the opposite side. For an 85 MW fire, this equals heat release rate of approximately 4.4 MW on the side which is further away from the fire.

Furthermore, it was found that when there is wind present and the fire is located near centreline, it can be assumed that 8.1 % of the *HRR* is occurring outside the side opening which is further away from the fire. For an 85 MW fire, this equals heat release rate of approximately 6.9 MW.

The visible height of a flame exposed to an area of interest (i.e. deck surface having LSAs) plays an important role in radiant heat flux to that area (Figure 1). Such visible flame height is calculated based on the deck height (for the first deck above the fire), by taking $H_{distance\ to\ deck} = H_{deck} - H_{opening\ midpoint}$ and $H_{visible\ flame} = H_f - H_{distance\ to\ deck}$. Visible flame height can be calculated in another suitable way also if the geometry does not suit the formula.

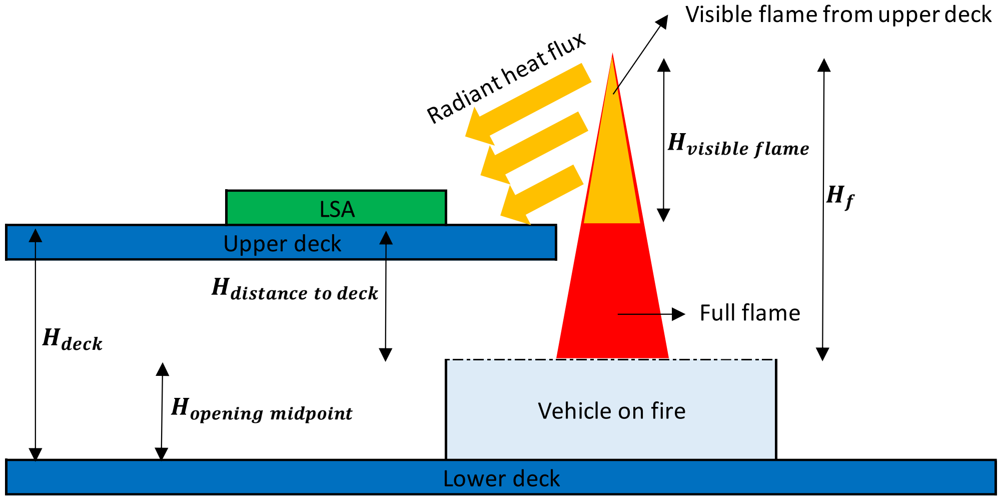

Figure 1. Schematic of visible flame from upper deck

To take into account the wind, it is proposed that the tilting of the flame is calculated based on the fire plume velocity at the height of the deck above $u_{deck\ edge}$ and the wind velocity u_{wind}. For simplification, the fire plume velocity is calculated based on the McCaffrey plume model (McCaffrey, 1979):

$$u_{deck\ edge}(z) = \kappa \left(\frac{z}{HRR^{2/5}}\right)^{\eta} HRR^{1/5} \quad (5)$$

where z is the vertical distance of interest (here taken from the opening midpoint) and κ and η are constants depending on the $\frac{z}{HRR^{2/5}}$. If $\frac{z}{HRR^{2/5}}$ is less than 0.08, κ is equal to 6.8 and η to 0.5. If $\frac{z}{HRR^{2/5}}$ is larger than 0.2, κ is equal to 1.1 and η to -1/3. Otherwise κ is equal to 1.9 and η to 0 (McCaffrey, 1979).

The plume tilt angle α can be calculated from $\tan(\alpha) = u_{deck\ edge}/u_{wind}$. It can then be approximated that due to the presence of wind, the radiation source should be moved by $d_{shift} = H_{distance\ to\ deck}/\tan(\alpha)$. Then, the total required safety distance can be taken as the sum of $d_{flame-target}$ and d_{shift}.

5.1.3 Example calculations with the modified analytic method

Scenario 1 from LASH FIRE T11.10: no wind, fire location near the side opening:

The fire inside has a maximum heat release rate of 85 MW, and the fire outside the ship on the non-fire side has a *HRR* of approximately 4.4 MW. The fire equivalent diameter is 4.9 m, calculated based on the side opening size (width 6.8 m, height 2.8 m). The corresponding flame height from the opening is 3.0 metres, of which 0.2 m is visible to the deck above (deck height 5.9 m, opening midpoint height 3.1 m). The width of the fire wall is 6.8 m (i.e. total width of the openings). Flame emissive power is 52.8 kW/m^2, and the view factor is equal to 0.179. Thus, at 0.2 metres from the fire, the received radiative heat flux is 9.5 kW/m^2.

Scenario 2 from LASH FIRE T11.10: 7.5 m/s headwind, fire location near the centreline:

The fire inside has a maximum heat release rate of 85 MW, and the fire outside the ship on the non-fire side has a *HRR* of approximately 6.9 MW. The fire equivalent diameter is 4.9 m, calculated based on the side opening size (width 6.8 m, height 2.8 m). If the flame was oriented vertically, the corresponding flame height from the opening would be 4.0 metres, of which 1.2 m would be visible to the deck above (deck height 5.9 m, opening midpoint height 3.1 m). The width of the fire wall is 6.8 m (i.e. total width of the openings). Flame emissive power is 52.8 kW/m^2, and the view factor is equal to 0.185. Thus, at 1.1 metres from the fire, the received radiative heat flux is 9.8 kW/m^2. The wind velocity is 7.5 m/s, and at the deck edge (2.8 m from opening midpoint) the plume centreline velocity is 11.1 m/s. The resulting velocity vector is oriented at an angle of 56°. The shifting of the radiation source by the wind is then 1.9 metres. The total safety distance required is then 1.1 m + 1.9 m = 3.0 m.

5.1.4 Summary of the results with different models

Safety distances for side openings based on the updated analytical method and LASH FIRE T11.10 CFD simulations (Hakkarainen et al., 2021) are presented in Table 1. The safety distance from side openings proposed in FIRESAFE II using criterion of maximum radiant heat flux of 2.5 kW/m^2 was 6 metres (Leroux et al., 2018). This distance is comparable to the distance calculated in the presence of headwind for maximum radiant heat flux of 2.5 kW/m^2.

Table 1. Safety distances for the side openings based on the updated analytical method and LASH FIRE T11.10 CFD simulations (Hakkarainen et al., 2021).

Safety distance based on radiant heat flux	**Proposed analytical method**	**LASH FIRE T11.10 CFD simulations, 85 MW***
Scenario 1: no wind, fire location near the side opening (location no. 2)		
Safety distance for < 2.5 kW/m^2	1.1 m	1.1 m
Safety distance for < 10 kW/m^2	0.2 m	0.3 m
Scenario 2: headwind (7.5 m/s), fire location near the centreline (location no. 4)		
Safety distance for < 2.5 kW/m^2	7.5 m	7.5 m
Safety distance for < 10 kW/m^2	3 m	1.5 m

** Includes additional 50 % on top of the simulation result, based on the known bias and error of the model*

5.1.5 Limitations of the proposed analytical method

The proposed analytical method has at least the following limitations:

- Only one ship geometry has been considered. It has not been investigated to what extent the proposed method is applicable to ships with different arrangements, such as side openings with different width.
- It has been noted that the scenarios where the fire is located near the ship's centreline lead to the largest required safety distances. The girders of the ship have an effect on the result in these scenarios. The proposed method might not be applicable to ships which have girders different from the example ship.
- Different sea areas can have different typical conditions. Only a limited number of different wind speeds has been considered. The proposed method might not be applicable to scenarios which have higher apparent wind.

5.2 Fire near an end opening

5.2.1 The calculation method proposed in FIRESAFE II

The following procedure parts regarding incident radiant heat flux proposed in FIRESAFE II (Leroux et al., 2018) are used:

Calculation of the incident radiant heat flux (SFPE, 2002):

$$Q_{inc} = E \cdot F_{f\to t} \tag{6}$$

where Q_{inc} is the incident radiant heat flux, *E* the average flame emissive power, and $F_{f\to t}$ the view factor.

Calculation of average flame emissive power *E* (Beyler & Shokri, 1989):

$$E = 58 \cdot 10^{-0.00823 \cdot D} \tag{7}$$

where *D* is the equivalent fire diameter (Heskestad, 1997):

$$D = \frac{HRR}{4 \cdot 320 \cdot H_{cargo}} \tag{8}$$

Calculation of view factor as in (SFPE, 2002):

$$F_{f\to t} = \frac{1}{2\pi}\left(\frac{x}{\sqrt{1+x^2}} arctan\left(\frac{y}{\sqrt{1+x^2}}\right) + \frac{y}{\sqrt{1+y^2}} arctan\left(\frac{x}{\sqrt{1+y^2}}\right)\right) \tag{9}$$

where $x = \frac{H_{visible\ flame}}{d_{flame-target}}$ and $y = \frac{w_{flame}}{d_{flame-target}}$.

The flame height can be calculated as Heskestad (1983):

$$H_f = 0.235 \cdot HRR^{\frac{2}{5}} - 1.02 \cdot D \tag{10}$$

HRR can be calculated as:

$$HRR = \dot{m}'' \cdot \Delta H_c \cdot A \tag{11}$$

The equivalent cargo material was assumed to have weight of 7488 kg, heat of combustion of 19.95 MJ/kg and mass burning rate of 15.61 g/m^{2}s (Arvidson, 1997). As a result, the heat release rate is 35 MW, flame height approx. 6.2 metres and flame emissive power 48.79 kW/m^2 (Leroux et al., 2018). The $d_{flame-target}$ is varied, until the incident radiative heat flux is within acceptable limits.

The generic ship studied in FIRESAFE II had the following dimensions: height to above deck 5.5 metres, height of truck cargo 3.0 metres and height of truck wheels 1.2 metres. As a result, the height of visible flame $H_{visible\ flame}$ was equal to 4.8 metres. The resulting safety distances were 13 metres with safety criterion of 2.5 kW/m^2 and 8 metres with safety criterion of 5.0 kW/m^2 (Leroux et al., 2018).

5.2.2 Modifications proposed to the FIRESAFE II approach

To obtain safety distances for maximum heat release rate of 85 MW, the calculation method for obtaining equivalent diameter had to be changed as the used method gave negative flame lengths for such large heat release rate. Equation for calculating the flame length was kept the same as in FIRESAFE II. Approximations were made for flaming area based on the known dimensions of the burning cargo, and a new equivalent fire diameter was calculated.

As mentioned in FIRESAFE II, the 35 MW fire corresponds to three halves of cargo units burning (Leroux et al., 2018). If the equivalent diameter of the fire is calculated based on the cargo height (3.0 m) and the heat release rate as in Eq. 11, then *D* is equal to 9.1 m. However, calculating *D* based on an equivalent diameter for a given area, we obtain *D* equal to 5.2 m. This is based on the assumption of top surfaces of three half cargo units burning, assuming burning length of 3 metres and width of 2.4 metres. This yields a visible flame length of 9.2 metres (i.e., the length of the flame which is visible above the first deck above the fire) when the fire heat release rate is 35 MW. The total flame length is 1.3 metres more than the visible flame length, the difference corresponding to the height difference between the top of the truck and the deck above. As it can be noted from Eq. 10 that the flame height is dependent on *HRR* and *D*, substituting *HRR* = 35 MW and *D* = 9.1 m or *D* = 5.2 m in it will lead to different flame heights and thus different visible flame heights. The difference in length of the visible flame was 4.0 metres when D was taken as 9.1 m and 5.2 m. This emphasizes the importance of different assumptions about the equivalent diameter of the fire on the visible flame height.

For an 85 MW fire, the geometry of the truck was kept the same as in LASH FIRE T11.10, reported in IR11.7, i.e., the width was 2.4 metres and the length 16 metres. The obtained visible flame length was 13.6 metres. The assumptions about deck height, wheel height or fire wall width were not changed from the original values used in FIRESAFE II.

Otherwise, the radiant heat flux and safety distance calculations were carried out similarly as in FIRESAFE II. The resulting safety distances were 18–20 metres with safety criterion of 2.5 kW/m^2, 11–12 metres with safety criterion of 5.0 kW/m^2 and 5–9 metres with safety criterion of 10.0 kW/m^2, for fires with heat release rates between 35 and 85 MW, respectively.

5.2.3 Summary of the results with different models

Safety distances for end openings based on radiant heat flux from FIRESAFE II (Leroux et al., 2018), the updated analytical method, and LASH FIRE T11.10 CFD simulations (Hakkarainen et al., 2021) are presented in Table 2.

Table 2. Safety distances for the end openings based on a radiant heat flux for FIRESAFE II (Leroux et al., 2018), the updated analytical method and LASH FIRE T11.10 CFD simulations (Hakkarainen et al., 2021).

Safety distance based on radiant heat flux	FIRESAFE II	Updated analytical method, 35 MW	Updated analytical method, 85 MW	LASH FIRE T11.10 CFD simulations, 85 MW*
Safety distance for < 2.5 kW/m^2	13 m	18 m	20 m	20 m
Safety distance for < 5 kW/m^2	8 m	11 m	12 m	12 m
Safety distance for < 10 kW/m^2	n/a	5 m	5 m	9 m

** Includes additional 50 % on top of the simulation result, based on the known bias and error of the model*

5.2.4 Limitations of the proposed analytical method

The proposed analytical method has at least the following limitation:

- Only one ship geometry has been considered. It has not been investigated to what extent the proposed method is applicable to ships with different arrangements.

6 Other methods

Main author of the chapter: Nikhil Verma, VTT

An alternative approach to the use of the analytical formula has been discussed in Annex A. It is based on the simulation results where different fire sizes and their effect on safety distances have been evaluated to check any quantifiable relationship between them. As demonstrated in Annex A, it is clear that with increasing fire sizes, the safety distances linearly increase. With such linear growth, a linear regression model can be developed to determine safety distances for different fire sizes.

Annex B covers a parametric study on the combined effect of different fire sizes with different opening widths. It has been demonstrated that the size of the openings has a considerable effect on radiant heat flux around openings. Smaller fires with bigger openings can have the same impact as larger fires with smaller openings. A large fire with a relatively small opening size can reduce the impact of fire in the area of interest. On the other hand, a small fire with a rather large opening size can increase the impact of fire in the area of interest. Such dependency can be utilized to select an optimum opening size concerning the perceived risk of fire in a critical area.

7 Conclusion

Main author of the chapter: Nikhil Verma, VTT

An analytical method has been formulated to find safe distances around or near openings on a ship. With the limitations mentioned earlier, the method can be applied to different fire sizes to calculate incident radiant heat fluxes and resulting safety distances. Another outlined method based on linear regression utilizing the simulation results can be an alternative way to find safe distances against different fire sizes. Such a method directly calculates safe distances for different fire sizes without requiring numerous intermediate calculations. Both methods can be further developed and tested for ships with different geometry.

Furthermore, a parametric study on the combined effect of different fire sizes with different opening widths has indicated that smaller openings reduce the effect of radiation around it. Thus, risk reduction measures can also include the flexibility to dimension the openings in critical areas practically smaller in size, in conjunction with ventilation requirements for the deck having such openings. Such steps will limit the effect of radiation. A further study can include the effect of openings of different sizes with different environmental conditions at sea.

8 References

M. Arvidson. (1997). Large scale ro-ro vehicle deck fire test, NORDTEST Project 1299-96, BRANDFORSK Project 421-941.

C. L. Beyler and M. Shokri. (1989). Radiation from larger pool fires. SFPE Journal of Fire Protection Engineering.

M. K. Cheong, W. O. Cheong, K. W. Leong, A. D. Lemaire and L. M. Noordijk. (2014). Heat Release Rate of Heavy Goods Vehicle Fire in Tunnels with Fixed Water Based Fire-Fighting System. Fire Technology, vol. 50, no. 2, pp. 249–266.

T. Hakkarainen, A. Tissari, N. Verma, T. Kling and T. Korhonen. (2021). IR11.7 – Development, theoretical evaluation and preliminary assessment of safe ro-ro space openings. LASH FIRE Internal Report.

T. Hakkarainen, N. Verma, A. Viitanen and A. Temple. (2022.) D11.4 – Description and assessment of safe ro-ro space openings. LASH FIRE Deliverable.

T. Hakkarainen, T. Kling, T. Korhonen and A. Tissari. (2020.) IR11.3 – Definition of conditions for ro-ro space openings. LASH FIRE Internal Report.

G. Heskestad. (1983). Luminous heights of turbulent diffusion flames. Fire Safety Journal.

G. Heskestad. (1997). Flame Heights of Fuel Arrays with Combustion in Depth. Fire Saf. Sci., Proceedings of the Fifth International Symposium, pp. 427–438.

G. Heskestad (2016). Fire Plumes, Flame Height, and Air Entrainment. In M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts, and C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering (pp. 396–428). Springer New York.

M. J. Hurley. (2016). Thermophysical Property Data. In M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts, and C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering (pp. 3425–3475). Springer New York.

B.Y. Lattimer (2016). Heat Transfer from Fires to Surfaces. In M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts, and C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering (pp. 745–798). Springer New York.

J. Leroux, P. Mindykowski, F. Evegren, L. Gustin, J. Faivre, M. Frösing, J. Lottkärr, K. Ukaj and B. Vicard. (2018). FIRESAFE II, Containment and Evacuation, Final report.

B. J. McCaffrey (1979). Purely Buoyant Diffusion Flames: Some Experimental Results (NBSIR 79-1910). Center for Fire Research, National Engineering Laboratory, National Bureau of Standards, Washington, D.C.

Ministry of Infrastructure and Transport, Directorate General for Rail and Marine Investigations, 3^ Division – Marine Investigations. (2014). Fire on board of the ro-ro pax NORMAN ATLANTIC. 28 December 2014. Final Report. 164 p.

SFPE. (2002). Handbook of Fire Protection Engineering, 3rd Edition

9 Indexes

9.1 Index of tables

9.2 Index of figures

10 ANNEXES

10.1 ANNEX A Effect of different fire sizes on safe distances

In Task T11.10, various scenarios were checked using CFD based simulations to find the safe horizontal and vertical distances around side openings. Table 9 from the internal report IR11.7 is shown in Table 3 for reference.

Table 3. Fire scenarios and Fire locations

Scenario*	Wind	Fire location
1	No wind	(2)
2	Headwind	(4)
3	Headwind	(2)
7	Tailwind	(5)
8	Portside	(7)
9	Headwind	(1)
10	Tailwind	(3)
11	Low velocity wind (No wind)	(6)

*Scenario 3 gave similar results as scenario 4, 5 and 6 for headwind. Therefore, scenarios 4, 5 and 6 for are not mentioned/discussed further.

Safe horizontal distances were taken from Scenario 2, and safe vertical distances were taken from Scenario 11. Scenario 2 had a fire at location 4, and Scenario 11 had a fire at location 6, as shown in Figure 2. As openings are recommended not to be positioned below Life-Saving Appliances (LSAs), the safe vertical distances, irrespective of findings from various scenarios, cover the whole area above the openings where no LSAs are recommended.

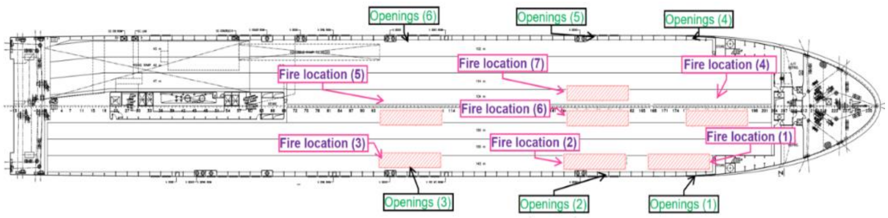

Figure 2. Side openings (openings (1, 2, 4, 5): 6 m x 3 m, openings (3, 6): 8 m x 3 m) and Fire locations

A fire with a maximum heat release rate of 85 MW was used, and the openings (laterally farthest from the fire) where the biggest contour of radiative heat flux was observed was considered for the calculation. It is again restated here that a fire close to openings will severely affect one side of a ship and will have a lesser impact on the other side of the ship. However, approximately centrally positioned fire (fire locations (4), (5), (6) and (7)) will have almost the same effect on both sides of openings on a ship. Thus, in such cases, LSAs kept near the openings on both sides can get almost equally damaged, leading to a very challenging evacuation situation.

To study the effect of fires of different sizes (different maximum heat release rates (HRR)), Scenario 2 was selected for further consideration. All the inputs and parameters were kept the same except the size of the fire. Fire sizes were varied from 35 MW to 85 MW, as shown in Table 4.

Table 4. Fire scenarios and Fire sizes

Scenario	Fire Size (Peak HRR)
1	35 MW
2	45 MW
3	75 MW
4	85 MW

For all scenarios, safe horizontal distances based on two radiant heat flux limits, i.e. 2.5 kW/m^2 and 10 kW/m^2 calculated from simulations, are presented in Table 5.

Table 5. Safe horizontal distances obtained from simulations

Scenario	Distance to < 2.5 kW/m^2 (m)	Distance to < 10 kW/m^2 (m)	Remark (if any)
1	6.2	0.9	Safety factor 1.5 is included in the calculation
2	7.4	1.7	
3	10.7	2.8	
4	12.0	3.0	

Safe horizontal distances with respect to fire size were plotted on a graph (Figure 3) to study the effect of fire size on safe horizontal distances. It is clear from Figure 3 that a linear relationship can be used for different fire sizes as an input to predict respective safe horizontal distances. Such a conclusion is based on the data analyzed and Stena Flavia generic ship model used.

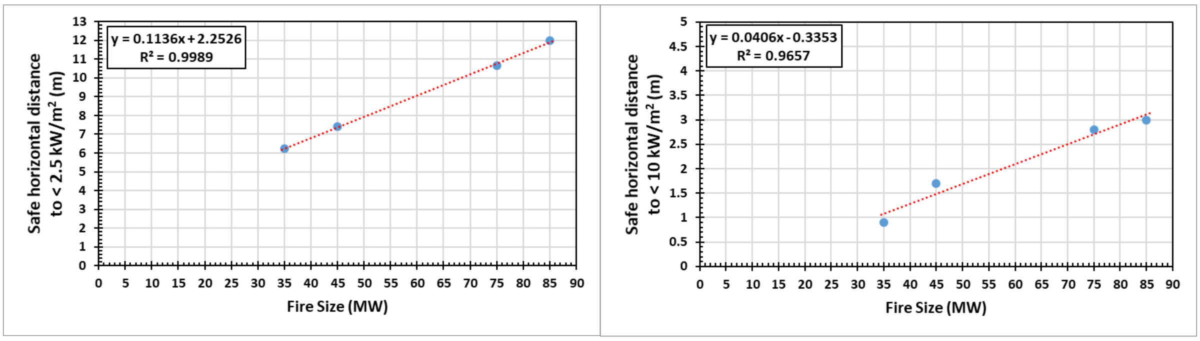

Figure 3. Graph of Safe horizontal distances vs Fire sizes

Table 6 shows the comparisons between safe distances obtained from the simulations and the linear model. To address the uncertainty of the model, standard error (assumed to be normally distributed) has been included as follows:

$$\boldsymbol{D_{2.5} = 0.11(FS) + 2.25 \pm e}$$

$$\boldsymbol{D_{10} = 0.04(FS) - 0.34 \pm e}$$

where $D_{2.5}$ denotes distance to < 2.5 kW/m^2 (m) and D_{10} denotes distance to < 10 kW/m^2 (m) from an opening based on linear model. *FS* denotes fire size in MW, *e* denotes standard error, and *e* = 0.1 for $D_{2.5}$ and *e* = 0.2 for D_{10}.

Table 6. Comparison of safe distances obtained from simulations and linear regression with standard error

Fire size (MW)	**Distance to < 10 kW/m² (m) from simulation (D_s)**	**Distance to < 10 kW/m² (m) from linear regression (D_{10})**	**Standard error in linear model (±e)**	**$D_{10} - e$**	**$D_{10} + e$**
35	0.9	1.1	0.2	0.9	1.3
45	1.7	1.5		1.3	1.7
75	2.8	2.7		2.5	2.9
85	3	3.1		2.9	3.3

Fire size (MW)	**Distance to < 2.5 kW/m² (m) from simulation (D_s)**	**Distance to < 2.5 kW/m² (m) from linear regression ($D_{2.5}$)**	**Standard error in linear model (±e)**	**$D_{2.5} - e$**	**$D_{2.5} + e$**
35	6.2	6.2	0.1	6.1	6.3
45	7.4	7.3		7.3	7.5
75	10.7	10.7		10.7	10.9
85	12.0	11.9		11.8	12.0

From Table 6, it can be noted that one standard deviation ($D_{2.5} \pm e$ or $D_{10} \pm e$) applied to the distance obtained from the linear model properly covers the values obtained from the simulations with safety factors already included. The assumptions of such simulations are stated in IR11.7 and have to be considered to use the stated linear relationship. Furthermore, the linear model should not be applied to fire sizes below 35 MW or above 85 MW but only for intermediate fire sizes.

This method provides an alternative approach to calculate safe distances. Further work can include checking the linear relationship with more test cases. A similar approach can also be developed and applied to other ships' models having different geometry. Moreover, the outputs from analytical formula for different HRR (in particular the HRR outside openings) can also be fitted with either linear or polynomial curves. While doing such fitting, it is noteworthy to emphasize that the standard error in such models is an essential part of the predictive method to address uncertainties. Therefore, no attempt should be made to reduce standard error to zero by overfitting the data points with linear or polynomial curves.

10.2 ANNEX B Parametric study: Combined effect of different fire sizes and opening widths

A simplified approach was followed to study different fire sizes with different opening widths. A simple model of the ship (like Stena Flavia) constituting the openings and the decks above it was made for CFD simulations without the effect of wind (Figure 4). The objective was to quantitatively study the variation in the length of radiant heat flux contour. For this, the length of the radiant heat flux contour with a limit of 2.5 kW/m^2 across openings was chosen. The approach was conservative as obstructions were adiabatic to have the maximum effect of fire outside and around the openings. Peak heat release rate was developed in the simulations within 200 s and remained steady until 300 s, around which radiant heat flux was measured. Similarly to Scenario 2 as mentioned in section 10.1, the fire was at location 4 in the simulations, and radiant heat flux contour was studied for openings (4) as it was laterally farthest away from the fire location compared to openings (1).

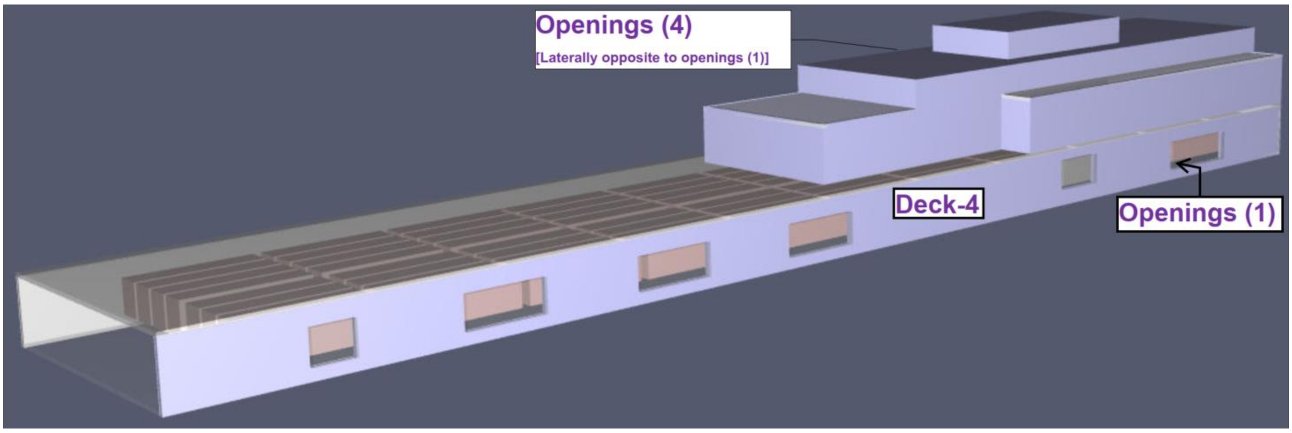

Figure 4. Model used in the simulation

The peak heat release rate (HRR) and the width of the openings (1) and openings (4) were varied as per the simulation matrix presented in Table 7.

Table 7. Variation of peak heat release rate and opening width in simulations

Serial No.	Peak HRR (MW)	Widths of Openings (1) and Openings (4)					
		2m	4m	6m	8m	10m	Simulation No.
1	35	1_2m	1_4m	1_6m	1_8m	1_10m	
2	45	2_2m	2_4m	2_6m	2_8m	2_10m	
3	55	3_2m	3_4m	3_6m	3_8m	3_10m	
4	65	4_2m	4_4m	4_6m	4_8m	4_10m	
5	75	5_2m	5_4m	5_6m	5_8m	5_10m	
6	85	6_2m	6_4m	6_6m	6_8m	6_10m	

A total of 30 simulations were run to check and quantify the effect of different fire sizes and opening widths on the radiation contour around the openings (4).

Table 8 shows the length of radiation contour with a limit of 2.5 kW/m^2 spanning across Openings (4) for various simulations. It can be noted that for a given fire size, as the width of the openings increases, the length of the radiation contour spanning across the openings also increases. Moreover, for a given openings width, as the fire size increases, the length of radiation contour also increases. For more insights from such data, values of length of radiation contour were standardised with the base value of **15.66,** which is the value of 85 MW fire size and 10 m openings width. Standardised values are presented in Table 9.

Table 8. Length of radiation contour with a limit of 2.5 kW/m² spanning across Openings (4)

	Width of Openings (1) and Openings (4)					
Peak HRR (MW)	**2m**	**4m**	**6m**	**8m**	**10m**	
35	4.16	5.97	7.94	9.56	11.62	*Length of radiation contour with limit of 2.5 kW/m² spanning across openings(4)*
45	4.66	6.96	9.22	10.91	12.43	
55	5.92	8.01	10.21	11.79	13.22	
65	6.90	9.12	10.71	12.81	14.09	
75	7.30	9.50	11.63	13.35	14.88	
85	8.22	10.35	12.73	14.51	**15.66**	

It can be noted from Table 9 that a 35 MW fire with a 6 m opening width led to the same standardized value (0.51) as that with a 55 MW fire with a 4 m opening width. Similarly, a 35 MW fire with an 8 m opening width led to the same standardized value (0.61) as that with a 75 MW fire with 4 m opening width. Some of the other values are also close to each other.

Table 9. Standardized values of length of radiation contour with a limit of 2.5 kW/m² spanning across Openings (4)

	Width of Openings (1) and Openings (4)					
Peak HRR (MW)	**2m**	**4m**	**6m**	**8m**	**10m**	
35	0.27	0.38	0.51	0.61	0.74	*Standardised values with base value of 15.66*
45	0.30	0.44	0.59	0.70	0.79	
55	0.38	0.51	0.65	0.75	0.84	
65	0.44	0.58	0.68	0.82	0.90	
75	0.47	0.61	0.74	0.85	0.95	
85	0.52	0.66	0.81	0.93	1.00	

Furthermore, Table 10 shows the overall percentage change in the length of radiation contour with a limit of 2.5 kW/m² spanning across Openings (4). It can be noted that for smaller fire sizes, an increase in the width of openings will lead to a more significant change in the length of radiation contour across openings (179 %) compared to the change in fire size with smaller opening widths (98 %). Moreover, if the width of the openings is already large, then a change in the size of the fire will lead to a smaller change in the length of radiation contour across openings (35 %) compared to the change in openings width with a larger fire size (91 %).

Table 10. Percentage change in length of radiation contour with a limit of 2.5 kW/m^2 spanning across Openings (4)

	Width of Openings (1) and Openings (4)					
Peak HRR (MW)	**2m**	**4m**	**6m**	**8m**	**10m**	**Percentage change**
35	4.16	5.97	7.94	9.56	11.62	179 %
45	4.66	6.96	9.22	10.91	12.43	167 %
55	5.92	8.01	10.21	11.79	13.22	123 %
65	6.90	9.12	10.71	12.81	14.09	104 %
75	7.30	9.50	11.63	13.35	14.88	104 %
85	8.22	10.35	12.73	14.51	15.66	91 %
Percentage change	98 %	73 %	60 %	52 %	35 %	

Based on the findings, it is apparent that the size of the openings has a considerable effect on radiant heat flux around openings. Smaller fires with bigger openings can have the same impact as larger fires with smaller openings. A large fire with a relatively small opening size can reduce the impact of fire in the area of interest. On the other hand, a small fire with a rather large opening size can increase the impact of fire in the area of interest. Such dependency can be utilized to select an optimum opening size concerning the perceived risk of fire in a critical area. Therefore, among other risk reduction measures, such measures can also include the flexibility to dimension the openings in critical areas as practically possible, in conjunction with ventilation requirements for decks.