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Deliverable D11.4

Description of development and assessment of safe ro-ro space openings

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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. In this report, the safe arrangement of ro-ro space openings in relation to critical areas on board ro-ro vessels is studied.

Simulations of fires in ro-ro spaces of two generic ships were performed using Fire Dynamics Simulator software to study heat transfer and smoke spread from ro-ro space side and end openings to critical areas. The studied scenarios included a heavy goods vehicle fire in different locations, and wind direction and speed were varied. Separate criteria were established for human and material safety.

To validate simulation results, large-scale testing was undertaken to provide comparative temperature and radiation measurements for a fire plume from an opening. Although general trends were similar, the experimental results did not provide a close correlation with the simulation results, due to smaller fire source in the tests compared to the simulated fire and differences in geometry.

A test series assessing the critical heat flux for ignition for a selection of materials used in life-saving appliances was performed. The critical heat fluxes measured were of the same order of magnitude as the critical limits assumed in simulations.

Based on the fire simulation results, potential risk control measures to establish a safe design for ro-ro space openings were identified and discussed. Implementing safety distances between the ro-ro space openings and critical areas seems to be an effective way to ensure safety of the critical areas. In newbuilds, the safety distances could be implemented by means of novel ship designs. For existing ships, the safety distances could be established by either closing some openings or by fitting some of the openings with suitable closure devices. In addition, manoeuvring can be used to direct smoke away from the critical areas in case of fire if conditions are favourable.

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Content

1 Executive summary

1.1 Problem definition

The main goal of LASH FIRE 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. This report, linked with Tasks 11.9, 11.10 and 11.11, presents the development and assessment of safe ro-ro space side and ventilation openings, in order to establish safe design including safety distances and arrangement of openings.

The work in these tasks is also 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*.

1.2 Technical approach

The regulatory, environmental, operational and shipyard requirements for ro-ro space openings and fire containment have been discussed on the basis of input obtained from LASH FIRE WP4 Formal Safety Assessment and WP5 Ship Integration (internal reports IR04.11 and IR05.12).

Simulations of fires in ro-ro spaces of two generic ships have been performed using Fire Dynamics Simulator (FDS) software to study heat transfer and smoke spread through ro-ro space side and end openings. Based on the results, safe design, including safety distances and arrangements of openings in relation to adjacent and critical areas, in particular Life-Saving Appliances (LSAs) and embarkation stations, has been established. This includes establishment of safety criteria based on material data or human critical conditions.

Small-scale fire tests of different LSA materials have been carried out to establish their critical conditions. Large-scale fire tests have been carried out to validate radiation heat transfer simulations of fire exposure from ro-ro space openings.

D11.4 has received input from IR11.3 (Definition of conditions for ro-ro space openings) where the regulatory, environmental, operational and shipyard requirements for ro-ro space openings and fire containment were reviewed, IR11.7 (Development, theoretical evaluation and preliminary assessment of safe ro-ro space openings) where simulations of fires in ro-ro spaces were performed to study heat transfer and smoke spread through ro-ro space side and end openings, and IR11.12 (Fire test and validation of results of safe design with ro-ro space openings) establishing critical conditions for LSA materials and providing validation of radiation heat transfer simulations of fire exposure from ro-ro space openings.

D11.4 provides input to D11.5 (Elucidation and guidelines for ro-ro space ventilation in case of fire), which will describe the definition of conditions, establishment, and validation of ro-ro space ventilation and smoke extraction.

1.3 Results and achievements

Based on the fire simulation results, potential risk control measures to establish safe design with ro-ro space openings have been identified and discussed. Implementing safety distances between ro-ro space openings and critical areas seems to be an effective way to ensure the safety of the critical areas. In newbuilds, the safety distances could be implemented by means of novel ship designs. For existing ships, the safety distances could be established by closing some openings. In addition, manoeuvring can be used to direct smoke away from the critical areas in fire situations if conditions are favourable.

Critical conditions of a limited selection of LSA materials have been established in small-scale fire tests. The critical heat fluxes measured are of the same order of magnitude as the criteria used for materials in simulations, indicating that the assumed values were reasonable.

Large-scale fire tests have been carried out to validate radiation heat transfer simulations of fire exposure from ro-ro space openings. Although general trends were similar, the large-scale test results did not provide a close correlation with the simulation results, either directly via temperature and radiation levels, or via the change in profile with height. The variation of exposure with height is likely due to the fact that small changes in geometry can have significant influences on the plume behaviour even for fires of the same size.

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 deliverable 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 deliverable contributes both to the objective of Action 11-C and the objectives of the LASH FIRE project. The results can be used to support decision making and revision of internal IMO regulations. In addition, the identified risk control measures can be used to improve fire safety of both newbuilds and existing ships. The results can also be directly used by end users and shipyards to guide design of ships and operations.

1.5 Exploitation and implementation

The obtained simulation results and the proposed risk control measures can be used to develop ro-ro space opening design guidelines. The results supplement the previous studies made on the topic, and as such they support decision making. The results, and the revised design guidelines based on them, can be used to design more fire-safe ro-ro ships or to improve the fire safety of existing ships.

The results can be used to revise international IMO regulations and support decision making. Safer designs with ro-ro space openings would improve management of fires on ro-ro ships and increase the overall fire safety of ro-ro ships.

2 List of symbols and abbreviations

Symbols

ε	Surface emissivity (dimensionless)
σ	Stefan-Boltzmann constant (W/m^{2}K)
$\dot{q}''_{inc}$	Radiant heat flux (W/m^2)
h_c	Convective heat transfer coefficient (W/m^{2}K)
T	Temperature (K)
t	Time (s)
C	Specific heat capacity (J/m^{2}K)

Abbreviations

CFD	Computational Fluid Dynamics
Circ.	Circular
CO	Carbon Monoxide
FDS	Fire Dynamics Simulator, a CFD code
H1	Horizontal distance from a side edge of openings to the point receiving radiant heat flux less than 10 kW/m^2
H2	Horizontal distance from a side edge of openings to the point receiving radiant heat flux less than 2.5 kW/m^2
HGV	Heavy Goods Vehicle
LSA	Life-Saving Appliances
MES	Marine Evacuation System
MOB	Man overboard
MSC	Maritime Safety Committee
PT	Plate thermometer
Ro-ro cargo ship	Cargo ship with ro-ro spaces or special category spaces
Ro-ro space	Ro-ro spaces are vehicle spaces into which vehicles can be driven
SOLAS	Safety of life at sea
TC	Type K thermocouple
V1	Vertical distance from top edge of openings to the point receiving radiant heat flux less than 10 kW/m^2
V2	Vertical distance from top edge of openings to the point receiving radiant heat flux less than 2.5 kW/m^2
V3	Vertical distance from bottom edge of openings to the point receiving radiant heat flux less than 10 kW/m^2
V4	Vertical distance from bottom edge of openings to the point receiving radiant heat flux less than 2.5 kW/m^2

3 Introduction

Main author of the chapter: Nikhil Verma, VTT

This report is based on the objective to eliminate significant containment weaknesses considering smoke, fire, and heat integrity failure through ro-ro space openings. It provides ro-ro space openings design guidelines by assessing risks of smoke and heat transfer from ro-ro space openings to Life-Saving Appliances (LSAs), adjacent areas, and ventilation inlets. The goal is to establish such a design for ro-ro space openings that any heat or smoke spreading from the ro-ro space to outside does not endanger any critical areas that can have any life-saving equipment, air inlet points, embarkation stations, etc. Such a safe design could be established, for example, by implementing safety distances around ro-ro space openings in critical areas or changing the opening arrangement in critical areas.

Different fire scenarios have been studied by performing simulations based on Computational Fluid Dynamics (CFD) to assess the impact of fire, smoke, and heat on prescribed tenable conditions for humans and thermally-safe conditions for construction materials of LSAs. This led to establishing safety distance criteria such that the humans and LSAs remain safe for evacuation due to fire on board.

Furthermore, this report also covers the results of the tests done to check the thermally-safe conditions for construction materials of LSAs and validation work for radiation heat exposure around ro-ro space openings obtained in fire simulations.

4 Conditions for ro-ro space openings

Main author the chapter: Tuula Hakkarainen, VTT

Fires in ro-ro spaces encompass the risk of spread of smoke and heat through ro-ro space side and end openings to life-saving appliances, adjacent areas, and ventilation inlets. Through the openings, the fire also receives oxygen. Other issues that were noted by the hazard identification in the FIRESAFE II project were the following (Leroux et al., 2018):

- If the space is not sub-divided, an uncontrolled ro-ro space fire may involve the whole length of the ship. The fire will quickly grow intense and could last for a very long time;
- On general ro-ro cargo ships, fire insulation (A-30) is required between decks, but this is not required on Ro-pax ships (except every 10 meters in height). If there is no insulation between decks (not required in Ro-pax ships, except every 10 meters in height), fire vertical spread after about 10 minutes is possible (without extinguishing system activated);
- Flame spread through openings or heat transfer through the deck may cause fire spread to the weather deck, which is associated with high risk since there are no fixed means for extinguishment and the accessibility for safe manual firefighting is limited.

To identify the essential requirements for ro-ro space openings and fire containment, the regulatory, environmental, operational and shipyard requirements were reviewed in the LASH FIRE project. As a result of the consolidation of the requirements, necessary functions for ro-ro space openings and fire containment were established.

4.1 Consolidation of the requirements

In order to establish necessary functions for ro-ro space openings and fire containment, the regulatory, environmental, operational and shipyard requirements were consolidated. Conflicting requirements from the different aspects were also discussed.

4.1.1 Regulatory requirements

The review of regulatory requirements included the documents listed in Table 1.

Table 1. List of documents used for the review of regulations.

IMO Documents	SOLAS Convention, as amended
	MSC.1/Circ.1615, Interim Guidelines for minimizing the incidence and consequences of fires in ro-ro spaces and special category spaces of new and existing ro-ro passenger ships
IACS & Class Rules	IACS Blue book dated January 2019
	BV Rules for Steel Ships (NR467), as amended in July 2019
	DNVGL Rules for the Classification of Ships, December 2019
	LR Rules and Regulations for the Classification of Ships, July 2019
Flag Administration Rules	MMF (French Flag Administration) Division 221 “Passenger ships engaged in international voyages and cargo ships of more than 500 gross tonnage”, 28/12/17 edition

As per definition, for a space to be considered an open ro-ro space, either both ends of the space need to be open or if only one end is open, then at least 10 % of the space sides need to be open. These openings cannot in practice be located below any survival craft or immediately adjacent to them. In addition, openings cannot be located immediately adjacent to embarkation stations, accommodation spaces, service spaces, and control stations, but locations below such areas are not prohibited. However, SOLAS II-2/20 requires that a fire in the cargo spaces located below these types of areas may not endanger them. MSC.1/Circ.1615 recommends a safety distance of more than 6 m measured horizontally between a cargo space side opening and survival craft, Marine Evacuation Systems (MES), survival craft embarkation stations, and muster stations.

4.1.2 Environmental conditions

Elimination of side openings would have a positive effect on fire safety, reducing the risk of fire spread and the effects of smoke gases on evacuees and the environment. On the other hand, closure of the openings would have also negative environmental impacts, such as increased fuel consumption and decreased cargo capacity due to additional vessel weight, and more air pollution due to slow-down of fleet renewal.

4.1.3 Operational conditions

Due to natural ventilation, having a mechanical ventilation system is not required in an open cargo space, which reduces costs as well as fire risks and environmental impacts. From the perspective of operational conditions, the capacity for dangerous goods is limited if the open ro-ro cargo space is prohibited, as IMDG Code prohibits carrying such goods in closed ro-ro spaces. In this case, the value of a “small” weather deck aft of a closed ro-ro cargo space will increase.

Shutters on side and aft/fwd openings have been discussed. The environment is very demanding for the shutters with constant salt spray, ice/snow, and wind. The function of the device must be very robust to work under all circumstances and to minimize the required maintenance. For such application, manual local emergency operation is a poor option since shutting must take place when fire/smoke is already a fact. Closing devices for side openings do not have any operational impact but those for fwd/aft ends of the cargo space do: the solution will influence movement and stowage of vehicles. It is noted that practical closing devices for marine applications are not available on the market.

Ventilation of toxic gases is essential for the well-being of the crew, firefighters and passengers. However, care must be taken to prevent them from leaking into public spaces (such as halls, dining rooms, and lounges) through openings in the side of the ship or through the fire doors in the ro-ro cargo space. Other openings should also be considered: mooring, bunker boat mooring, accommodation ladder, pilot access, access to man overboard (MOB) boat, access to LSA equipment, and bunkering operation.

4.1.4 Shipyard requirements

From the design and production aspect, the purpose of the design is to fulfil the regulations, to enable efficient cargo operations, and to minimize the steel weight. The regulatory requirements concern the minimum size for a space to be considered an open ro-ro space and for enabling efficient natural ventilation, the structural strength requirements, and the restrictions for the positioning of the openings. The positioning of the openings should also support the cargo operations and efficient stowage of the cargo.

4.1.5 Conflicts between requirements

The regulatory restrictions on the positioning of the openings partially conflict with the design objective of maximizing the size of the openings, which is important from both operational and environmental aspect. This issue can be, however, addressed through arranging the critical areas and the openings relatively far away from each other. Safety concerns caused by the openings could also be addressed by adding closure methods, which could be activated after a fire has been detected in the cargo space. However, adding such closure devices would in turn increase the ship's lightweight and needs for maintenance. Increase of the ship's lightweight would have a negative environmental effect by both increasing fuel consumption and reducing the possible deadweight.

4.1.6 Necessary functions for ro-ro space openings and fire containment

Necessary functions identified for ro-ro space openings and fire containment are summarized in Table 2. In normal conditions, having large side and end openings in ro-ro cargo spaces has many positive effects. However, the openings should be designed in such a manner that they do not endanger critical areas, e.g., survival craft stowage areas or embarkation stations, during exceptional circumstances such as a fire in the cargo space.

Table 2. Necessary functions for ro-ro space openings and fire containment.

Requirement	Description
Ventilation	For naturally ventilated open ro-ro spaces, either 10 % of the sides or both ends need to be open. Care must be taken to prevent toxic gases from leaking into public spaces (such as halls, dining rooms, and lounges) through openings. If the space is not an open ro-ro space, mechanical ventilation is needed.
Robustness of closing devices	Function of the closing devices, e.g., shutters on side and aft/fwd openings, must be very robust to work under all circumstances and to minimize the required maintenance. Shutting must be possible also in fire conditions. Closing system will influence movement and stowage of vehicles.
Enabling efficient cargo operations and sufficient dangerous goods capacity	Permanent openings at the end(s) of the cargo space are required to enable both passage and efficient use of space with stowed cargo. If the open ro-ro cargo space is prohibited, dangerous goods capacity is limited and the value of a "small" weather deck aft of a closed ro-ro cargo space will increase.
Openings may not interfere with other equipment and systems	Openings are not allowed below embarkation stations for MES or other survival craft launching areas.
A fire in the cargo space may not endanger survival craft stowage areas and embarkation stations	Openings are not allowed immediately adjacent to survival craft stowage areas, embarkation stations, accommodation spaces, service spaces and control stations. MSC.1/Circ.1615 recommends at least 6 m horizontal distance between a cargo space side opening and survival craft, Marine Evacuation Systems (MES), embarkation stations and muster stations.

5 Heat and smoke transfer simulations

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

Simulations of fires in ro-ro spaces of two generic ships have been performed using Fire Dynamics Simulator (FDS) software. The aim was to study heat transfer and smoke spread through ro-ro space side and ventilation openings to establish safe design with ro-ro space openings. The simulations and their results have been described in detail in the LASH FIRE internal report IR11.7 (Hakkarainen et al., 2021).

5.1 Simulation scenarios and setup

5.1.1 Methodology

The simulations were performed using a Computational Fluid Dynamics (CFD) code, namely, Fire Dynamics Simulator (FDS). A heavy goods vehicle (HGV) fire was considered as the design fire in the simulations. The design fire curve is based on an experiment by Cheong et al. (2014), where the drencher system was operated 8 minutes after the detection of the fire. This was considered to correspond to a scenario with delayed response.

Most of the simulations were made with wind, which was simulated as coming from different directions. The wind speed used in the simulations, 7.5 m/s, corresponds to both the 50-year average of the southern Baltic Sea and the 10-year average of the central Baltic Sea.

The safety of the designs was assessed using the life safety performance criteria presented in MSC.1/Circ.1552. Based on the simulations, the radiant heat flux criterion was the most critical one. For unprotected humans, the limiting value based on MSC.1/Circ.1552 is 2.5 kW/m^2. Based on the literature review carried out, 10 kW/m^2 is considered as the critical heat flux for ignition of the material used in LSAs. For equipment where passengers are also involved (assuming without thermal protections), radiant heat flux should not exceed 2.5 kW/m^2.

In the simulations with wind, the computational domain shall be large enough in comparison to the ship size to allow undisturbed wind flow over the ship. Especially, the domain shall be long along the wind direction. An example of a computational domain for a headwind scenario with Magnolia Seaways is shown in Figure 1. In the simulations without wind, a domain with reduced size was used.

Based on the mesh sensitivity studies, the cell size of 20 cm in the vicinity of the fire was sufficient to capture the fire plume accurately enough. The cell size was gradually increased when going further away from the fire, with the largest cell size being 3.2 m.

The fire development was simulated for 1200 seconds. The wind field was allowed to stabilize for at least 200 seconds in the simulation, before the fire was included.

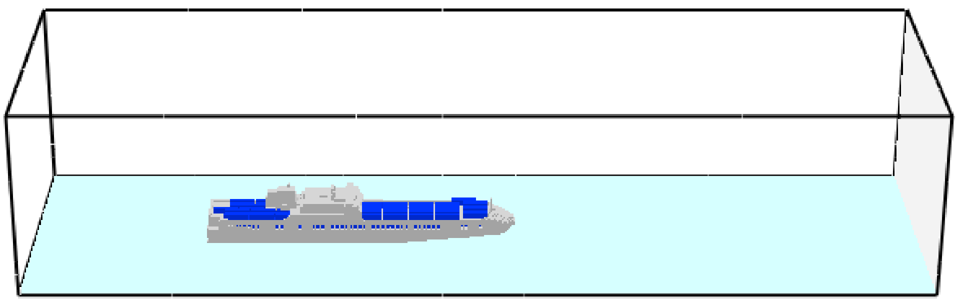


Figure 1. Example of a computational domain for a headwind scenario with Magnolia Seaways. (Hakkarainen et al., 2021)

5.1.2 Simulations: Stena Flavia

The geometry of the Stena Flavia simulation model is shown in Figure 2. The ship's external surfaces above the waterline are included in the model. In the open ro-ro spaces, also the girders have been included. All the openings are taken into account in the model in order to study the effect of wind on the smoke movement and transportation.

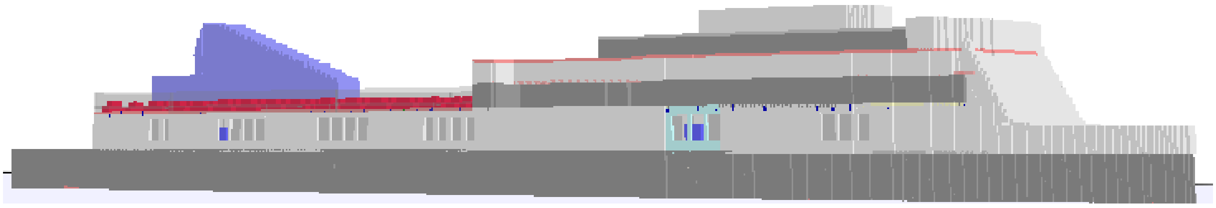


Figure 2. Stena Flavia simulation model. (Hakkarainen et al., 2021)

5.1.3 Simulations: Magnolia Seaways

The simulation model geometry of Magnolia Seaways is shown in Figure 3. The ship's external surfaces above waterline were included in the model. In the open ro-ro spaces, also the girders have been included. The open ro-ro spaces have been filled with simplified, rectangular geometries representing trucks in a fully loaded ship.

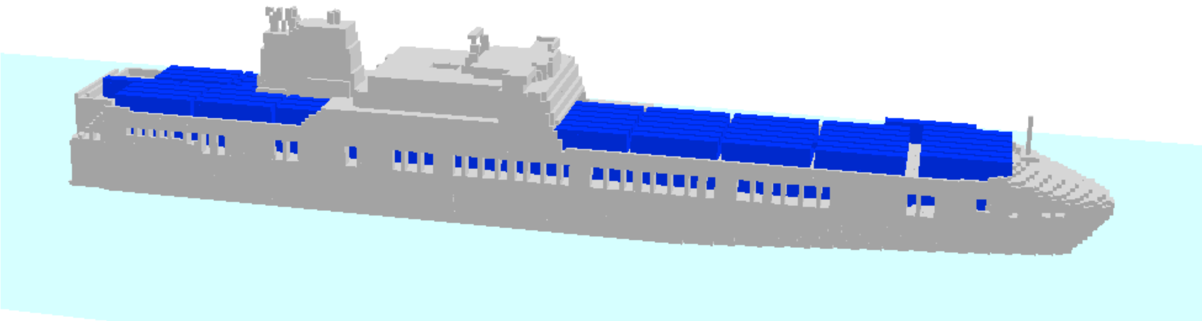


Figure 3. Simulation model geometry for Magnolia Seaways. (Hakkarainen et al., 2021)

5.2 Simulation results

It must be noted that the obtained simulation results presented in the following sections are dependent on the assumptions made about the ship's geometry, size of the fire, environmental conditions, and operational procedures. In the absence of specific information, many estimations have been made in this work to consider possible worst-case scenarios. As a result, the safety distances concerning such scenarios presented in this report should not be used as a design basis of any kind unless stated otherwise.

5.2.1 Stena Flavia

The area around the openings in the critical space of Stena Flavia has been observed to become unsafe in most of the scenarios considered in the simulations. The area around the openings where performance criteria (especially related to radiant heat flux, temperature, and visibility) have been exceeded spans across and over the multiple decks in simulations affecting LSAs. The periphery of such areas marks the limit of performance criteria such that any location inside the area is unsafe. Values of radiant heat flux exceeding the performance criteria around such openings primarily demarcate the safety distances to be considered for the safety of LSAs. Such safety distance demarcations are schematically shown in Figure 4, and Table 3 contains the respective values.

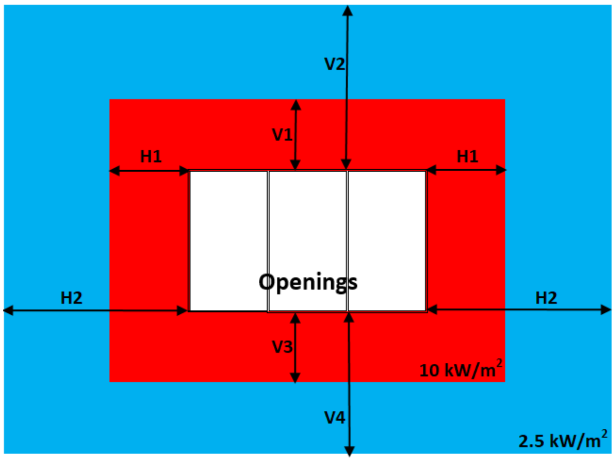


Figure 4. Sketch showing the parameters used to define the boundaries of unsafe areas for LSAs around the openings in terms of radiant heat flux limits evaluated in the simulations. The red area should not include any LSAs because the heat flux is higher than 10 kW/m², while the blue area can only include LSAs which do not involve passengers (e.g., life rafts launched directly into the water) because the heat flux is higher than 2.5 kW/m².

Table 3. Results of Stena Flavia simulations in terms of distances to areas with unsafe radiant heat fluxes. Parameters H1, H2, and V1 to V4 are those shown in Figure 4.

Wind	**Distance to < 2.5 kW/m² (m)**	**Distance to < 10 kW/m² (m)**
Headwind	H2=**7.5**; V2=9.1; V4=1.6	H1=**1.5**; V1=3.1; V3*=0
Tailwind	H2=3.4; V2=4.2; V4=0.5	H1=0.4; V1=0.6; V3=0
Portside/ Starboard side	H2=0; V2=0; V4=0	H1=0; V1=0; V3=0
No wind	H2=2.1; V2=**14.3**; V4=**2.0**	H1=0.5; V1=**5.4**; V3=0

* Value of zero (for V3) means that the limiting radiation contour is within the openings.

As the current SOLAS requirements and their interpretations prohibit openings below survival crafts and MES, the vertical distances represented by V1 and V2 should cover the full longitudinal space above such openings, thus prohibiting any placement of LSAs above them.

5.2.2 Magnolia Seaways

All the performance criteria were exceeded outside the superstructure in all the simulations. Unsafe conditions occurred in the open ro-ro space in all the simulations to a large extent. Compared to the performance criteria of temperature or CO, the criteria of radiant heat flux and visibility were exceeded in larger areas. More details regarding the radiant heat flux and visibility results are provided in Table 4 and

Table 5, respectively. Distance to a radiation heat flux less than 5 kW/m² is included as a reference. All distances are provided as horizontal distances from the ro-ro space opening.

Table 4. Results of Magnolia Seaways simulations in terms of horizontal distances to areas with unsafe radiant heat fluxes as shown in Figure 4. (Hakkarainen et al., 2021)

Wind	**Distance to < 2.5 kW/m² (m)**	**Distance to < 5 kW/m² (m)**	**Distance to < 10 kW/m² (m)**
Headwind	26.6 m*	16.6 m*	13.2 m*
Tailwind	14.2 m	6 m	3.8 m
Portside	9.6 m	5.4 m	4.2 m
Starboard side	15.2 m	9.4 m	6.8 m
No wind	14.4 m	9.8 m	7.4 m

* Instantaneous value downwind due to a shed eddy.

Table 5. Visibility results for Magnolia Seaways simulations. (Hakkarainen et al., 2021)

Wind	Distance to > 10 m visibility (m)
Headwind	45.2 m*
Tailwind	46.4 m*
Portside	23.6 m*
Starboard side	19.2 m*
No wind	14 m

* Instantaneous value downwind due to a shed eddy.

Instantaneous (downwind) values of mentioned quantities have been noted as there is randomness in their occurrence over large distances due to shed eddies.

5.3 Utilization of the results

Based on the study, two different methods were considered to be effective for improving the fire safety of ro-ro spaces: implementing safety distances between the ro-ro space openings and critical areas, and use of manoeuvring to avoid smoke spread to critical areas. However, manoeuvring the ship to suitable position might not be possible or the best course of action in all situations (Hakkarainen et al., 2021). Nevertheless, both options are to be explored for use to maximize safety for evacuation.

5.3.1 Safety distances for ro-ro space openings

Implementing safety distances between the ro-ro space openings and critical areas seems to be an effective way to ensure safety of such spaces. In newbuilds, the safety distances could be implemented by means of novel ship designs. For existing ships, the safety distances could be established by either closing some openings or by fitting some of the openings with suitable closure devices (Hakkarainen et al., 2021). Such safety distances are proposed based on the plausible worst-case scenario considered in FIRESAFE II project (Leroux et al., 2018) rather than based on the possible worst-case scenario considered in this study. It is emphasized here that all required actions must be taken to avoid the possible worst-case scenario as described in the LASH FIRE study of Hakkarainen et al., 2021.

The horizontal safety distances formed in FIRESAFE II project (Leroux et al., 2018) are shown in Table 6. In practice, as the current SOLAS requirements and their interpretations prohibit openings below survival craft and MES, the values for the vertical distances are not explicitly mentioned.

Table 6. Horizontal safety distances based on radiant heat flux criteria: results of FIRESAFE II project. (Leroux et al., 2018)

Safety distance based on radiant heat flux	FIRESAFE II
Safety distance for < 2.5 kW/m^2	13 m
Safety distance for < 5 kW/m^2	8 m

A possible alternative method for arriving at suitable safety distances could be the use of performance-based design. The suitable approaches could be either analytical calculation tools or advanced computational methods (such as CFD, e.g., using the methodology presented in the LASH FIRE study of Hakkarainen et al., 2021). Availability of analytical calculation tools would be beneficial since advanced computational methods are usually time-consuming. There are on-going efforts within LASH FIRE to advance in making analytical formulas for this purpose, but it is noted that such tools need to be well validated and approved.

5.3.2 Manoeuvring guidelines

Based on the simulation results, changing course to favourable direction can help to avoid smoke spread to critical areas. It should be noted, however, that manoeuvring can be impossible due to a blackout, and that while side wind is favourable in terms of avoiding smoke, it might be in contradiction with safe evacuation procedures. Some general recommendations for manoeuvring in case of a fire in an open ro-ro space are given below. Recommendations are given separately for fires near side and end openings.

Manoeuvering recommendations in case of a fire near side openings

- Identify the side of the ship (port side or starboard side) from where evacuation can be done, and take measures to ventilate smoke away from the critical area on that side. It is recommended to select the side of the ship that is located furthest away from the fire.
- Try to manoeuvre the ship to such direction that the critical area on the selected side has the least impact from fire products (smoke, radiant heat flux etc.).
- The least impact can be achieved in most situations if the selected side is manoeuvred to face the wind perpendicular to it (portside wind or starboard side wind).
- If manoeuvring the ship as mentioned above is not possible, then the following recommendations need to be explored for choosing a suitable direction for apparent wind:
    - If the fire is located aft from the critical area, then the suitable apparent wind is most likely headwind.
    - If the fire is located forward from the critical area, then the suitable apparent wind is most likely tailwind.
- Note that there can be smoke or stray smoke in the critical area even after manoeuvring as per recommendations. However, its impact would be less than the other side of the ship nearest to the fire.

It is proposed that the ship's individual manoeuvring guidelines include simple arrangement plans, which include the locations of the ro-ro space openings and the critical areas. An example figure for manoeuvring guidelines based on Stena Flavia, showing the ro-ro space openings and the critical areas (in green), is shown in Figure 5. Use of such figure(s) could help decision making in case of an emergency: in case of a fire, the fire location can be included in the plan (red dots), and the possible paths of the smoke can be analysed based on the existing wind conditions. To help identifying the location of the fire accurately, it is proposed to use, for example, frame numbers or numbering for the openings. However, these markings should also be clearly included in the ro-ro space, so that the locating can be easily done.

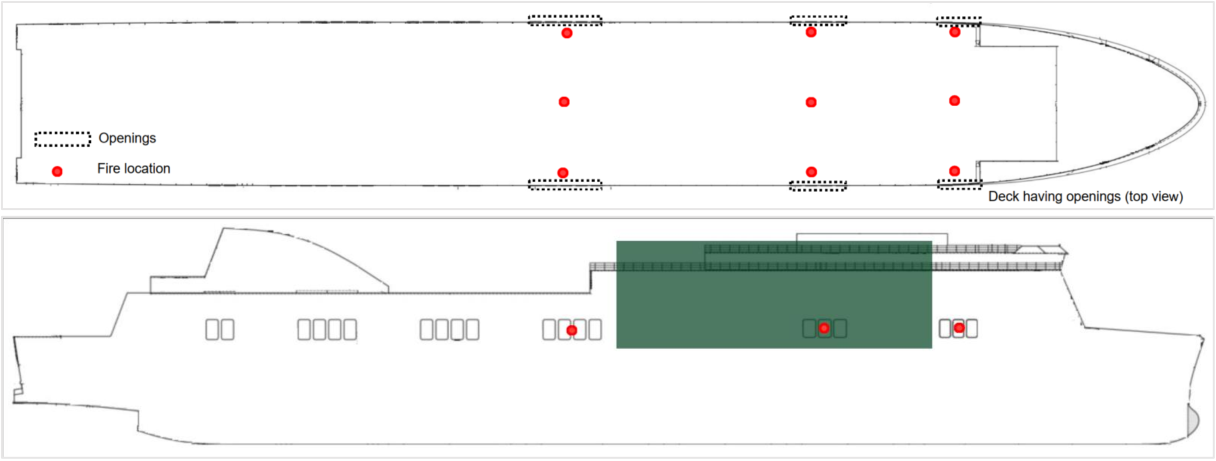


Figure 5. Example figure for manoeuvring guidelines based on Stena Flavia, which shows the ro-ro space openings and the critical areas (in green). In case of an emergency, the fire location can be included in the plan (red dots), and the possible paths of the smoke can be analysed based on the existing wind conditions.

Manoeuvring recommendations in case of a fire near an end opening

- After a fire has been confirmed onboard, assess if any smoke can be observed outside. If yes, locate the opening(s) where the smoke is coming from.
- If necessary, ventilate the smoke away from any critical areas such as assembly stations, LSA stowage areas and external evacuation routes by manoeuvring the ship if possible.
- Recommendations for choosing a suitable direction for apparent wind:
    - If the ro-ro space end opening producing the smoke is located aft from the critical areas to be protected, suitable apparent wind is most likely from headwind to sidewind.
    - If the ro-ro space end opening producing the smoke is located forward from the critical areas to be protected, suitable apparent wind is most likely from tailwind to sidewind.
    - The best wind direction will push the smoke directly away from the ship, and the smoke will not travel across any parts of the ship.
- Note that having a strong sidewind can cause the smoke recirculation back to the ship on the leeward side due to pressure differences.
- Note that if the end opening is protected from the wind by large structures such as casing, smoke ventilation will not be as effective.
- It is recommended to prioritize protecting those critical areas which are located furthest away from the fire. Those which are closest to the fire will more likely become unavailable due to the heat from the fire.

It is proposed that the ship's individual manoeuvring guidelines include simple arrangement plans, which include the locations of the ro-ro space openings and the critical areas. An example figure for manoeuvring guidelines based on Magnolia Seaways, showing the ro-ro space openings and the critical areas (in green), is shown in Figure 6. Use of such figure(s) could help decision making in case of an emergency: in case of a fire, the fire location can be included in the plan (red dots), and the possible paths of the smoke can be analysed based on the existing wind conditions. To help identifying the location of the fire accurately, it is proposed to use, for example, frame numbers or numbering for the openings. However, these markings should also be clearly included in the ro-ro space, so that the locating can be easily done.

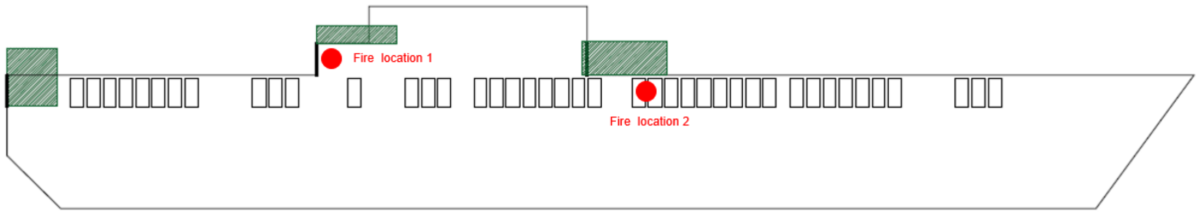


Figure 6. Example figure for manoeuvring guidelines based on Magnolia Seaways, which shows the ro-ro space openings and the critical areas (in green). In case of an emergency, the fire location can be included in the plan (red dots), and the possible paths of the smoke can be analysed based on the existing wind conditions.

6 Fire tests

Main author of the chapter: Alastair Temple, RISE

In order to assess the validity of the simulations, discussed in section 5 and detailed in IR11.7, a comparison against a real fire is needed to be made. In no wind condition simulations, values of radiative heat flux vertically above openings adjacent to the fire source were found to be 140 kW/m^2 and 75 kW/m^2 at 2 m and 4.5 m above the top edge of side openings, respectively. This exposure is very similar to that observed in the experiments which lead to the development of the SP-Fire 105 standard (Anderson et al., 2017) and therefore it was proposed that the SP-Fire 105 test is used to provide the data for simulation validation.

In addition to the above evaluation of the simulation results against experimental results, an evaluation was made to confirm whether the proposed limits on heat flux levels are appropriate for the materials used in the construction of LSAs. For T11.10, the critical heat flux for the ignition of LSA materials was assumed to be 10 kW/m^2, and it was assumed that the safe limit for egress routes and equipment where passengers are also involved (without thermal protection) should not exceed 2.5 kW/m^2 (International Maritime Organization, 2016). Small-scale experiments are therefore conducted to establish the critical heat fluxes for ignition of a selection of samples from different types of LSAs, as described in section 6.1.1.1.

6.1 Experimental

This section describes the experimental methodology for the small-scale experiments (establishing critical heat fluxes) and large-scale experiments (validating simulation results).

6.1.1 Small-scale tests

Experiments to establish the critical heat flux of a range of materials were carried out in the Cone Calorimeter following the requirements of ISO 5660-1:2019 Annex H (SIS/TK 181, 2019). The tested samples consisted of the materials listed in section 6.1.1.1 and were prepared in accordance with paragraph 8 of ISO 5660-1:2019 which can be summarised as follows:

- It is required to cut 10 cm square samples from the provided material.
- The samples are cut to be as flat as possible.
- If the sample is not flat, the highest point of the sample is placed at the centre of the sample.
- The sample should be wrapped in a single layer of aluminium foil (shiny side towards the sample) to cover the bottom and sides of the sample and extended +3 mm over the top of the sample. Where the samples are less than 6 mm thick, they should be placed on a refractory ceramic fibre blanket prior to being wrapped in foil.
- If the sample is wholly made of or has a top layer of plastic fabric, a mesh is placed over the sample to prevent the sample from “curling up” as it is heated.
- The samples are tested without a retainer frame (in accordance with Annex H of ISO 5660-1:2019 (SIS/TK 181, 2019)).

In conditions where radiative heating is dominant (i.e., remote from any flames), the orientation of the sample has a limited impact, thereby the experiments were carried out in a horizontal orientation only, as per the recommendations of Annex H of ISO 5660-1:2019. A sketch of the experimental setup can be seen in Figure 7 and a general picture of the cone calorimeter setup is shown in Figure 8.

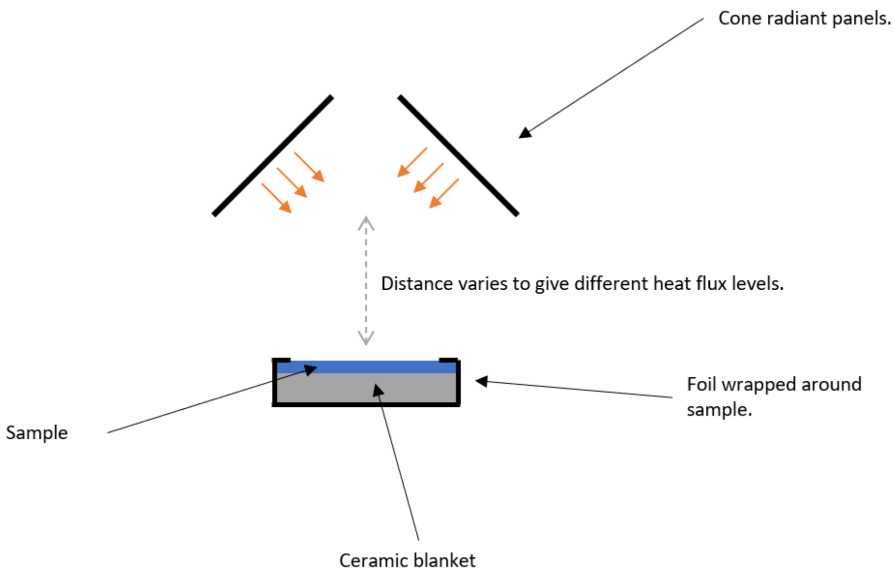


Figure 7. Sketch of cone calorimeter setup for establishing critical heat flux.

Figure 8. General set up of cone calorimeter experiments for establishing critical heat flux according to ISO 5660-1:2019.

The testing was conducted for both piloted and unpiloted ignition. For each series, the first heat flux used was 15 kW/m^2 after which it was adjusted with a step of 5 kW/m^2 and then with finer steps of 1 kW/m^2 until the limit was found. The heat flux was assumed not to cause ignition if no ignition occurred after 15 minutes of exposure, as recommended by ISO 5660-1:2019.

6.1.1.1 Selection of LSA materials

The selection of LSA materials available for evaluation was limited by their availability. The selected materials tested were as follows:

- The hard casing for storage of inflatable life rafts. This is a hard glass fibre reinforced plastic and was supplied by Centro Jovellanos (part of the Ministry of Transport, Mobility and Urban Agenda of Spain).
- Lifejackets. These are a composite of a plastic foam covered by a plastic fabric. The lifejackets were provided by Centro Jovellanos.
- Life raft lining. A black plastic fabric used as the outer lining of life rafts. The lining was provided by Survitec.
- Marine escape system lining. An orange plastic fabric used as the outer lining of marine escape systems. The lining was provided by Survitec.

6.1.2 Large-scale tests

The experimental data are based on results from façade testing carried out following the SP FIRE 105 test methodology (Swedish National Testing and Research Institute, 1994). The fire source for SP 105 fire tests is comprised of 60 litres of heptane in trays with flame suppressors and lasts 15-20 minutes. The method utilises a limited level of instrumentation, so extra instrumentation was added in addition to those specified in the test method to be able to compare the experimental results with the simulation results. Two tests were carried out by the addition of extra instrumentation onto commercial tests at RISE. Both tests were of similar insulated timber façade systems, although by different manufacturers. Therefore, there will be some additional contribution to the fire from the façade in addition to the main fire source which must be considered when making comparisons. The test set-up can be seen in Figure 9, and the locations of the additional instrumentation added for the purpose of this project are listed in Table 7 and illustrated in

Figure 10 to Figure 12. At each location, a plate thermometer (PT) and a separate K-type thermocouple were placed. All the PTs on independent stands were positioned facing towards the façade. For Test 1, the PTs projected through the false windows (locations 13, 15 and 16) and were faced away from the façade. For Test 2, the PTs were reversed to face toward the façade. This was due to the large volume of hot gases (flames and smoke) passing between the PTs and the façade rather than outside of them. Therefore, the sensitivity of the PTs to direction increases the discrepancy between the experimental and simulation results. Accordingly, combining the results of tests 1 and 2 may give a more comparable estimation of the heat flux when compared to the simulation results which considered the radiation exposure from 360-degree view angle.

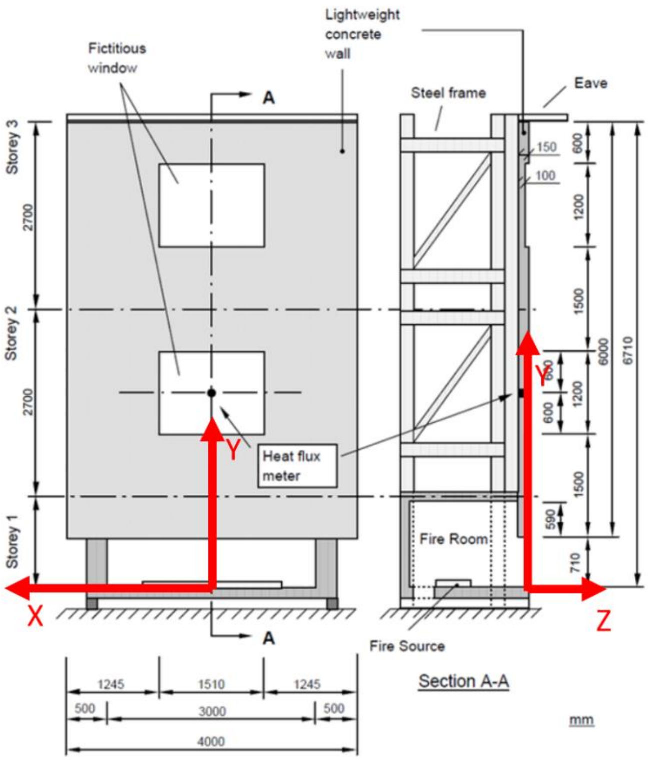


Figure 9. SP Fire 105 Test Rig showing axis for instrumentation locations, see Table 7.

Table 7. Instrumentation locations for large-scale tests. Each location has a plate thermometer and a K-type thermocouple. SP Fire 105 test specified Heat Flux Meter location also noted.

Location	Support	X	Y	Z
1	Stand 1	0	0.305	3.6
2	Stand 1	0	1.46	3.6
3	Stand 1	0	2.81	3.6
4	Stand 2	3	0.305	0.4
5	Stand 2	3	1.46	0.4
6	Stand 2	3	2.81	0.4
7	Stand 3	3	0.305	3.6
8	Stand 3	3	1.46	3.6
9	Stand 3	3	2.81	3.6
10	Stand 4	2	2.81	0.4
11	Stand 4	2	4	0.4
12	Stand 4	2	5.51	0.4
13	Lower Window	0	2.51	0.4
14	Lower Window	0	2.91	0
15	Upper Window	0	5.21	0.4
16	Upper Window	0	5.81	0.4
Heat Flux Meter	Lower Window	0	2.81	0

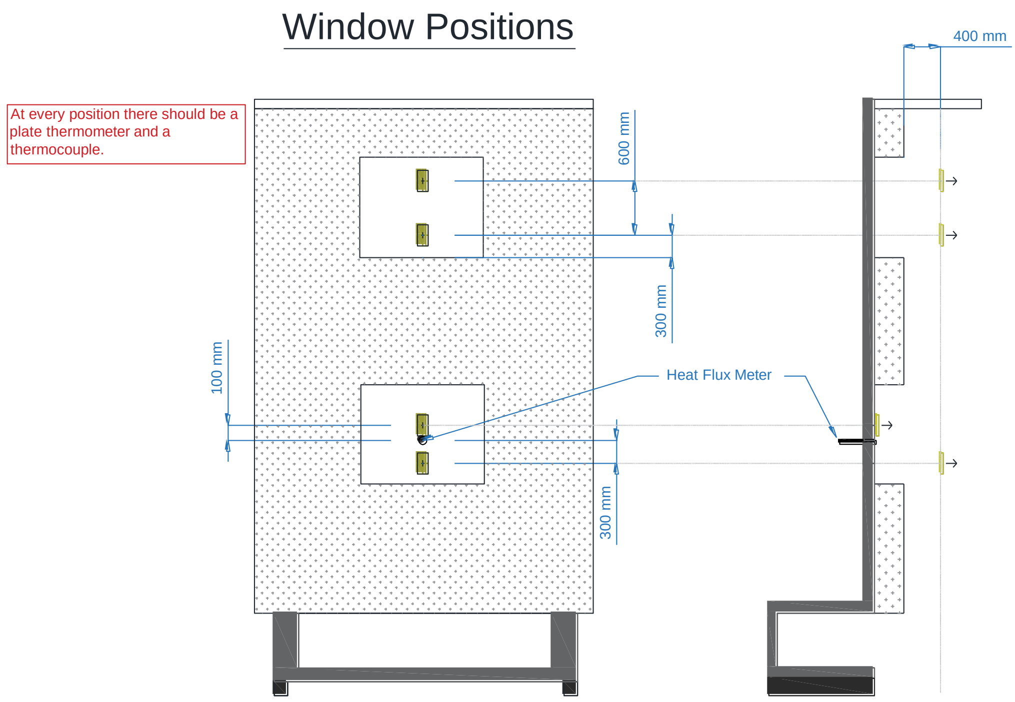


Figure 10. Illustration showing the locations of the instrumentation placed at the false windows. The PTs at 400 mm distance from the façade face away from the façade in Test 1, while they were reversed in Test 2 to face toward the façade, to account for the sensitivity of the PTs to direction.

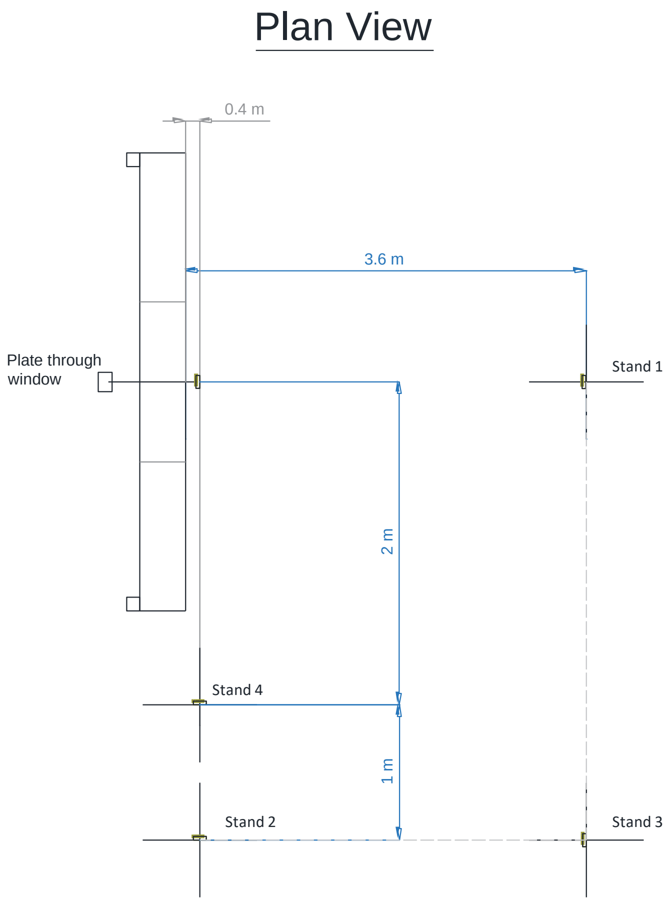


Figure 11. Plan view of instrument locations for the large-scale experiments.

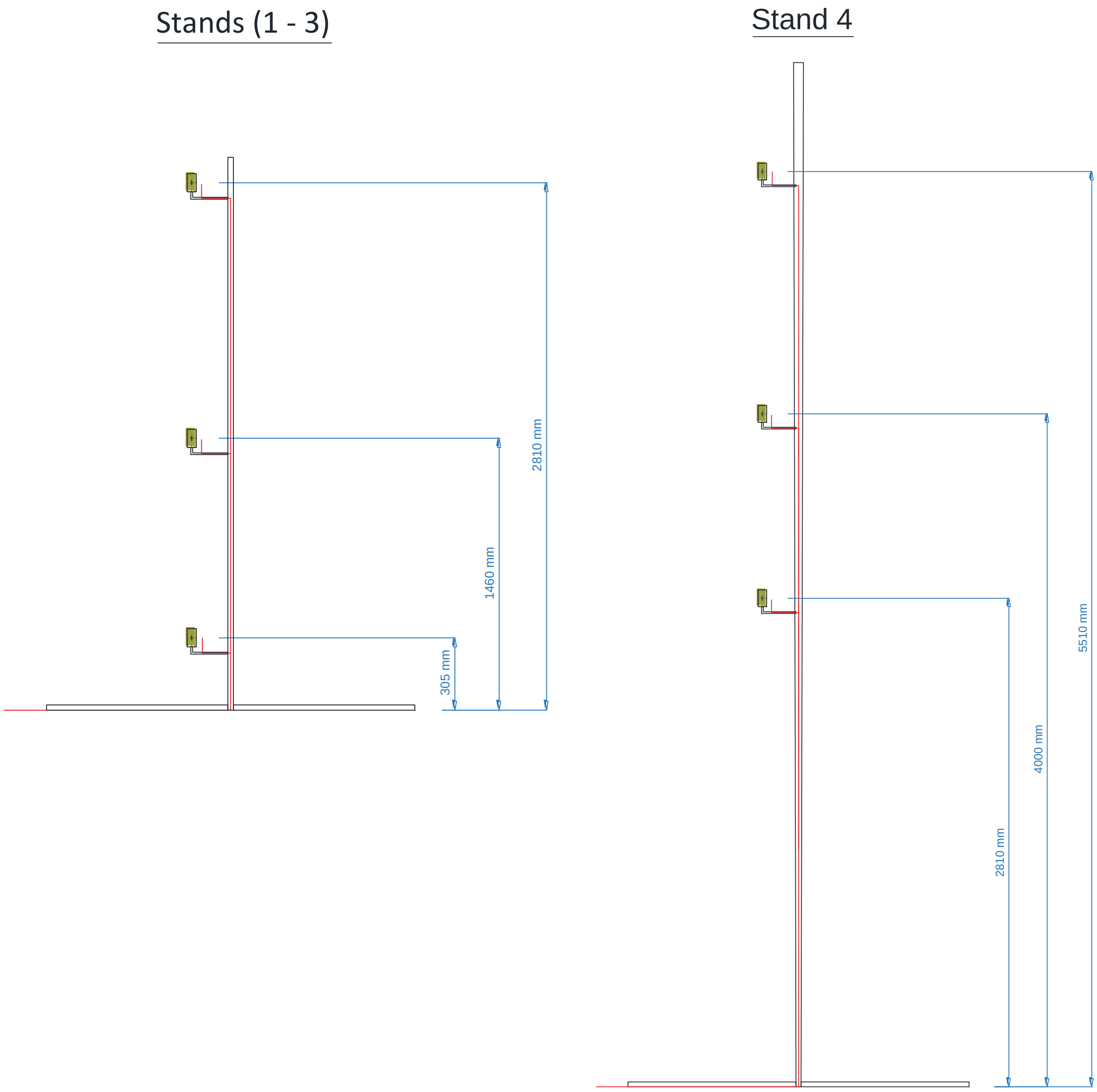


Figure 12. Illustrations showing the construction of the freestanding supports for the plate thermometers and thermocouples.

6.2 Test results

Summarised results from the experimental studies and a brief discussion of these can be found in the following sections. Full results for each study can be found in Annex A and Annex B for the small-scale and large-scale tests, respectively.

6.2.1 Small-scale tests

The small-scale critical heat flux experiments were conducted on a range of samples of materials commonly used for the construction of safety equipment. A full list of the material samples and the established critical heat fluxes can be seen in Table 8.

Table 8. List of cone calorimeter results and critical heat fluxes established.

#	Material Description	Use on ro-ro ship	Supplier	Manufacturer	Critical Heat Flux - Piloted†	Critical Heat Flux - Unpiloted†
1	Hard plastic reinforced with glass fibres	Storage casing for inflatable life rafts	Centro Jovellanos	Unknown	9 kW/m^2	23 kW/m^2
2	Plastic foam covered by a plastic fabric	Lifejacket	Centro Jovellanos	Unknown	*	
3	Black plastic fabric	Life raft lining	Survitec	Survitec	9 kW/m^2	21 kW/m^2
4	Orange plastic fabric	Marine escape system lining	Survitec	Survitec	11 kW/m^2	26 kW/m^2
* No ignition was recorded at heat fluxes of up to 20 kW/m^2, but there was significant damage to the internal material at heat fluxes as low as 2.5 kW/m^2. This damage would likely weaken the performance of the equipment significantly. † Critical heat flux is obtained as the arithmetic average of the lowest heat flux for ignition and the highest heat flux with no ignition.						

6.2.2 Large-scale tests

Plate thermometers are commonly used in fire resistance furnace tests as they allow measuring incident radiation heat flux in ambient air in an affordable robust way which enables the implementation of more sensors compared to the use of water-cooled heat flux gauges (Ingason & Wickström, 2005).

The irradiance to a plate in a known ambient environment (known gas temperature and convective heat transfer coefficient) can be assessed as:

$$\dot{q}''_{inc} = \varepsilon\sigma T_{PT}^4 + \frac{(h_c + K)(T_{PT} - T_g) + C\frac{\partial T_{PT}}{\partial t}}{\varepsilon}$$

where

$\dot{q}''_{inc}$ is the incident heat flux by radiation (W/m^2).
ε is the surface emissivity.
σ is the Stefan-Boltzmann constant (W/m^{2}K^4).
h_c is the convective heat transfer co-efficient (W/m^{2}K).
T is a temperature (K) with subscripts $_{PT}$ for plate thermometer and $_g$ for gas.
t is time (s)
C is the specific heat capacity of the plate thermometer (J/m^{2}K).

As most measurement locations are outside of the fire plume, and as the test is performed indoors where there will be minimal wind speed, the convective heat transfer coefficient is assumed to fixed at 12 W/m^{2}K. The correction parameters for the plate thermometers used are as defined in (Häggkvist, Sjöström, & Wickström, 2013), K = 8 W/m^{2}K, C = 4200 J/m^{2}K. The raw temperature data from the test and the calculated incident radiation histories can be found in Annex A while comparison of the peak radiation and gas temperatures can be seen in Table 9.

Table 9. Comparison of peak values recorded in the tests and simulation.

Location	SP 105 Test		Simulation	
	Peak Incident Radiation* (kW/m^2)	Peak Gas Temperature (°C)	Peak Incident Radiation (kW/m^2) (*adjacent; remote*)	Peak Gas Temperature (°C) (*adjacent; remote*)
13	53	600	153; 14	640; 255
15	14	290	50; 7	475; 147
16	11	270	45; 6	470; 136

Two values for peak incident radiation and the peak gas temperature have been taken from the simulation for comparison. The first value (larger value) was recorded at the openings adjacent to the fire, see Figure 13. The second value (smaller value) was recorded at the openings on the opposite side of the openings adjacent to the fire (Figure 13).

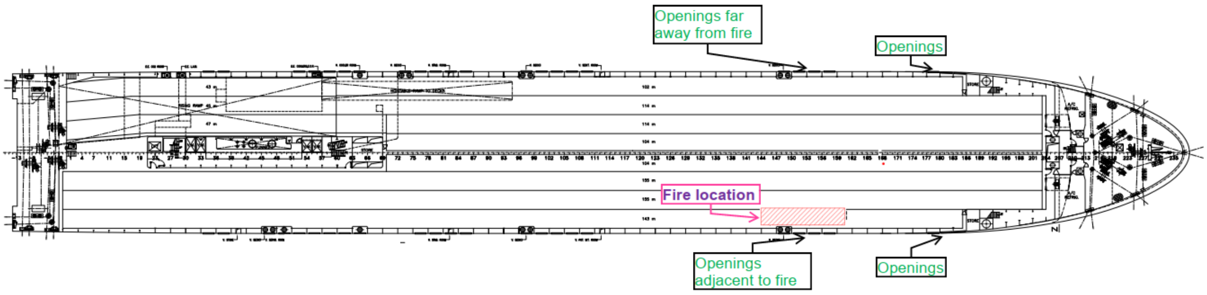
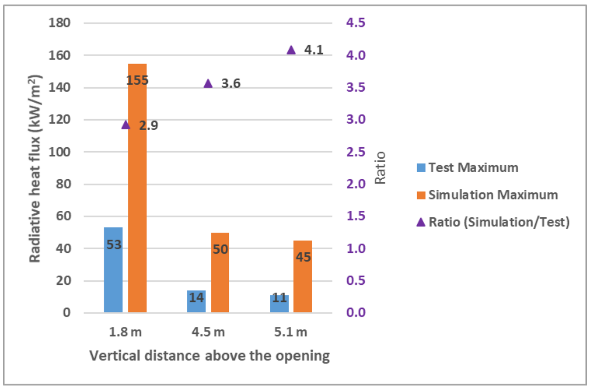


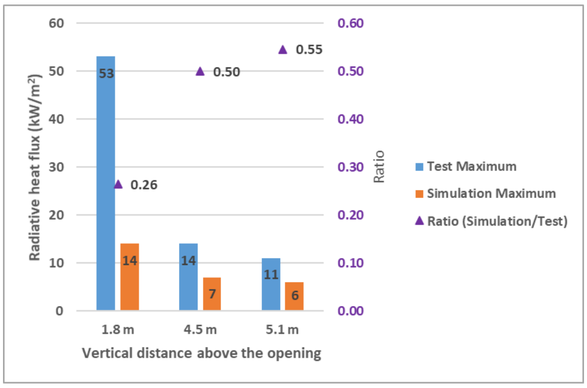
Figure 13. Openings adjacent to the fire and openings far away from the fire. The closer the openings are to the fire, the larger will be the radiative heat flux received on the outside surface around the openings.

For the openings that were further away from the fire, the recorded heat fluxes were comparatively lower than those recorded for the openings adjacent to the fire. As it is expected that any evacuation will take place from the side of the ship that is further away the fire, it is important to compare these values as well as those close to the fire location. This allows evaluating the heat fluxes likely at the location utilised for evacuation, i.e., where there must be usable LSA, rather than simply the maximum heat fluxes anywhere on the ship.

As radiative heat flux is the quantity of interest, Figure 14 shows the comparison of radiative heat fluxes between the tests and the simulation for the chosen locations. It can be noted that for the openings near the fire, the radiative heat fluxes obtained in the simulations were much higher than the ones obtained from the tests. In the chosen locations, the values obtained in the simulations ranged from 3 to 4 times (rounded estimates) of the values obtained in the tests. For the openings further away from the fire, the radiative heat fluxes obtained in the simulations were lower than the ones obtained from the tests. In the chosen locations, the values obtained in the simulations ranged from 0.3 to 0.5 times (rounded estimates) of the values obtained in the tests.



Case A: Openings near the fire



Case B: Openings away from the fire

Figure 14. Comparison of radiative heat flux from the tests and the simulation.

There are multiple reasons why there is a difference between the radiative heat fluxes from the simulation and the tests. Firstly, they have different fire sizes, and thereby different heat release rates and flame extensions from the opening. They also have different combustion chamber geometry and location of the fire relative to the opening. More specifically, the simulation fire is within a large ro-ro deck with sufficient ventilation to have combustion primarily in this space, although flames were up to 2.3 m high above the openings on the side close to the fire, while in the tests, the test chamber is much smaller, with significant external combustion. Finally, there is a difference in the combustion of the fuel (infinitely fast mixing controlled combustion model with 0.025 g/g soot yield and 0.15 g/g carbon monoxide yield used in the simulation), and thereby smoke concentration, soot yield and species generation, which will all affect the emitted radiative flux in the simulation and the tests. Furthermore, the non-uniformity in the trend (Simulation value/Test value) of radiative heat fluxes at different locations around an opening can be attributed to the subsequent difference in the plume height, plume radius and the centreline temperatures. This will in part be due to contributions of the timber facades tested, which will add heat directly into the fire plume due to the combustible nature of the timber, but additionally such parameters are also sensitive to the flow before the spill edge of the openings, the presence of the stands (shown in Figure 12), opening width causing the spillage, plume adherence to the wall, etc. Such unavoidable subtle geometrical differences between the set-up of the tests and that of the simulation are suspected of having significant impact in the non-uniformity in the trend of radiative heat fluxes.

Considering the large difference in heat fluxes between the test and the simulations, and the uncertainty of how representative the test may be of a ro-ro deck fire (differences between fire size, fuels, and geometry), it is recommended that the simulation results from a plausible worst-case scenario are used as the basis for any recommendations from the LASH FIRE project. This should minimise the risk of arriving at non-conservative recommendations that would lead to unsafe designs. Should further validation be performed in the future, the following items in order of increasing complexity and cost could be considered to provide additional confidence in the results:

1. Detailed review of the simulation design fire against a range of experiments and fires within the literature (may have already been completed in earlier work).
2. Conduct a secondary simulation to model the large-scale testing carried out in this project. This simulation should match the ro-ro ship simulation in terms of the computational aspects (e.g., mesh size). This can show that the underlying simulation setup is appropriate for modelling fire plumes from openings, and combined with confidence in the input fire for the main simulation, it can increase confidence in the results.

3. Develop and conduct a custom experiment specifically designed to match the fire conditions assumed within the ro-ro deck for the main simulation.

7 Safe design with ro-ro space openings

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

Based on the simulation results, the generic ship design can be made safer by implementing a safe area around openings based on safety distances. In practice, the safety distances can be established either by repositioning the openings away from the critical areas or by repositioning the critical areas away from the openings. Primary risk reduction potential of implementing safety distances between side and end openings and critical areas results from protecting people from smoke and heat and impeding fire propagation to LSAs and other critical areas. Primary cost items caused by implementing the safety distances are the investment costs for obtaining novel ship designs and the possible reduction in efficiency of operation and capacity of transport of dangerous goods.

The definition of proper safety distances is challenging, requiring further research 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 CFD models). There are on-going efforts within LASH FIRE to advance in making analytical formulas for this purpose. It is noted, however, that such tools need to be well validated and approved.

It has also been demonstrated that changing the ship's course to a favourable direction can help to avoid smoke spread to critical areas. It should be noted, however, that manoeuvring can be impossible due to a blackout, and that while side wind would be favourable in terms of avoiding smoke, it might be in contradiction with safe evacuation procedures. Primary risk reduction potential achieved by implementing ship emergency manoeuvring procedures also protects people on board from smoke effects and provides access to at least some LSAs during a fire. Primary cost items caused by implementing ship emergency manoeuvring procedures are the production costs of procedure guidelines and training costs of the crew. Guidelines should be prepared individually for each ship based on its geometry and construction features.

Both the abovementioned measures reduce the impacts of fire, smoke, and heat, making it possible to keep the conditions tenable for humans and thermally safe for LSA materials.

8 Conclusion

Main author of the chapter: Nikhil Verma, VTT

Simulations of fires in ro-ro spaces of two generic ships were performed using FDS software to study heat transfer and smoke spread from ro-ro space side and end openings to critical areas, such as embarkation stations and LSAs. The studied scenarios included an HGV fire in different locations and varied wind directions and speeds. Separate criteria were established for human and material safety.

The obtained simulation results are dependent on the assumptions made about the environmental conditions and operational procedures. Based on the simulation results, potential risk control measures to establish safe design with ro-ro space openings were identified and discussed.

Implementing safety distances between the ro-ro space openings and critical areas seems to be an effective way to ensure the safety of the critical areas and the safety equipment kept in them. In newbuilds, the safety distances could be implemented by means of novel ship designs. The safety distances for existing ships could be established by either closing some openings or fitting some of the openings with suitable closure devices. In addition, manoeuvring can be used to direct smoke away from critical areas if conditions are favourable.

To validate the results of the simulations, large-scale testing was undertaken to provide comparative temperature and radiation measurements for a fire plume from an opening. This was achieved by adding extra measurements to two SP-Fire 105 façade tests. Although general trends were similar, the experimental results did not provide a close correlation with the simulation results, either directly via temperature and radiation levels or via the change in profile with height. However, this was not totally unexpected, given that the fire source in the tests was smaller than the simulated fire and that small changes in geometry can have a significant influence on the plume behaviour, even for fires of the same size.

A test series assessing the critical heat flux for ignition, utilising the cone calorimeter, for a selection of materials used in LSAs was completed. The materials tested included two fabrics utilised in the construction of life rafts and marine evacuation equipment and hard glass fibre reinforced casing material used for storage of inflatable life rafts and materials from life jackets. Unpiloted ignition was not observed in any samples below 20 kW/m^2, while the critical heat flux for piloted ignition was established as low as 9 kW/m^2. No ignition was observed for the life jacket composite materials at heat fluxes below 20 kW/m^2, but there was significant damage to the internal foam at heat fluxes as low as 2.5 kW/m^2. These heat fluxes are of the same order of magnitude as the critical limits assumed in simulations, indicating that the previously assumed values are reasonable.

9 References

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10 Indexes

10.1 Index of tables

10.2 Index of figures

11 ANNEXES

11.1 ANNEX A – Full Experimental Results, Large-Scale Fire Test

This annex contains the full results from the large-scale SP Fire 105 tests undertaken in Borås. Details of the positions of each measurement location and the conduction methodology for the calculated incident radiant heat fluxes can be found in sections 6.1.2 and 6.2.2 of the report, respectively.

11.1.1 Raw Temperature Readings

Figure 15 to Figure 19 show the temperature histories of each plate thermometer (PT) and thermocouple (TC) for Test 1 while Figure 20 to Figure 24 show the same for Test 2.

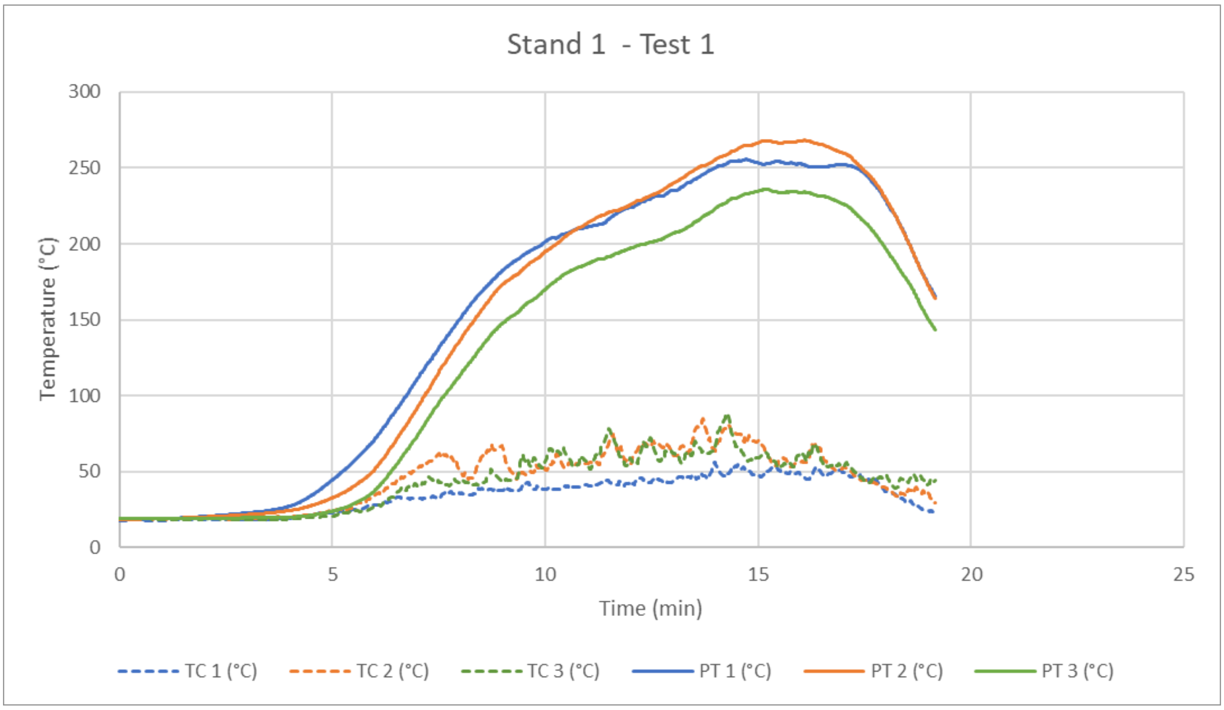

Figure 15. Temperature readings on Stand 1 (locations 1 to 3) – Test 1.

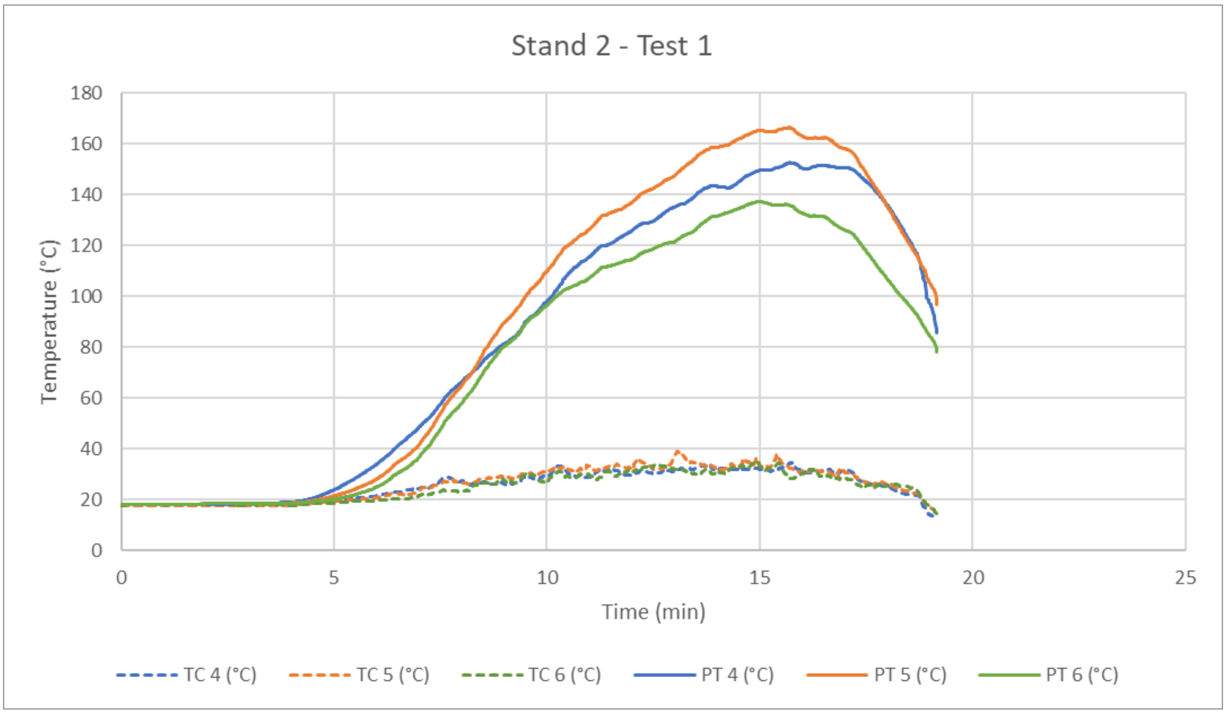

Figure 16. Temperature readings on Stand 2 (locations 4 to 7) – Test 1.

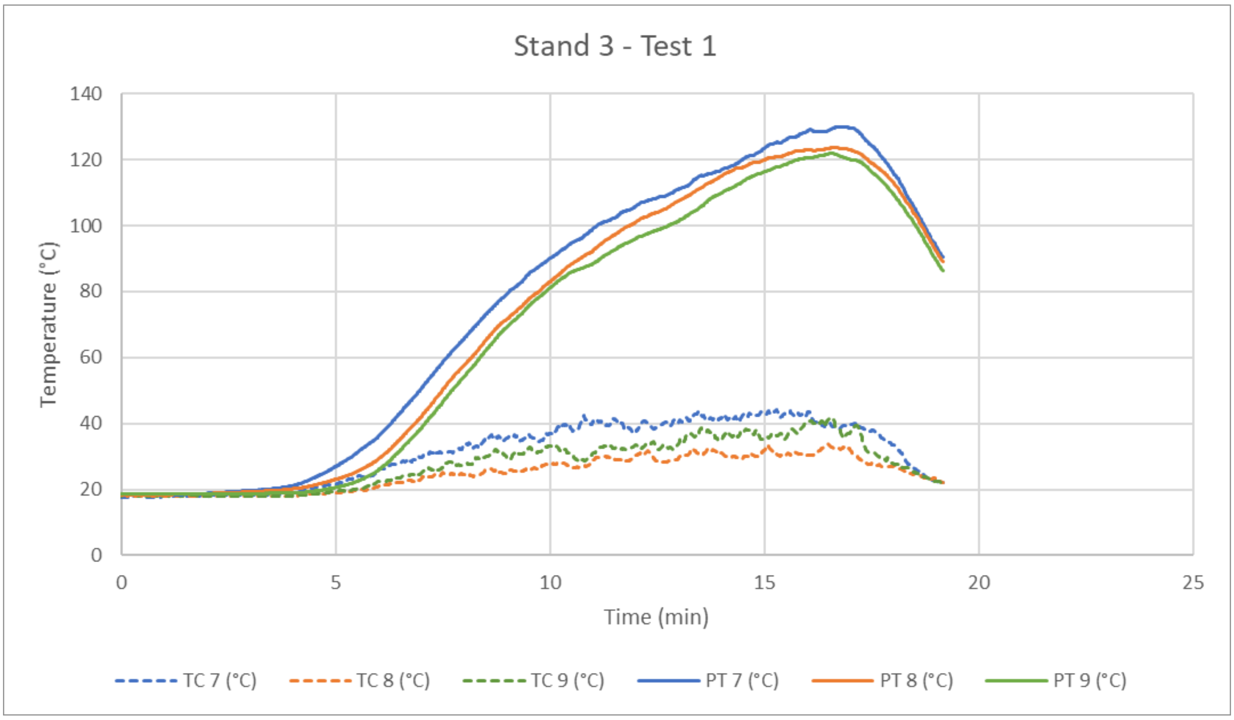

Figure 17. Temperature readings on Stand 3 (locations 7 to 9) – Test 1.

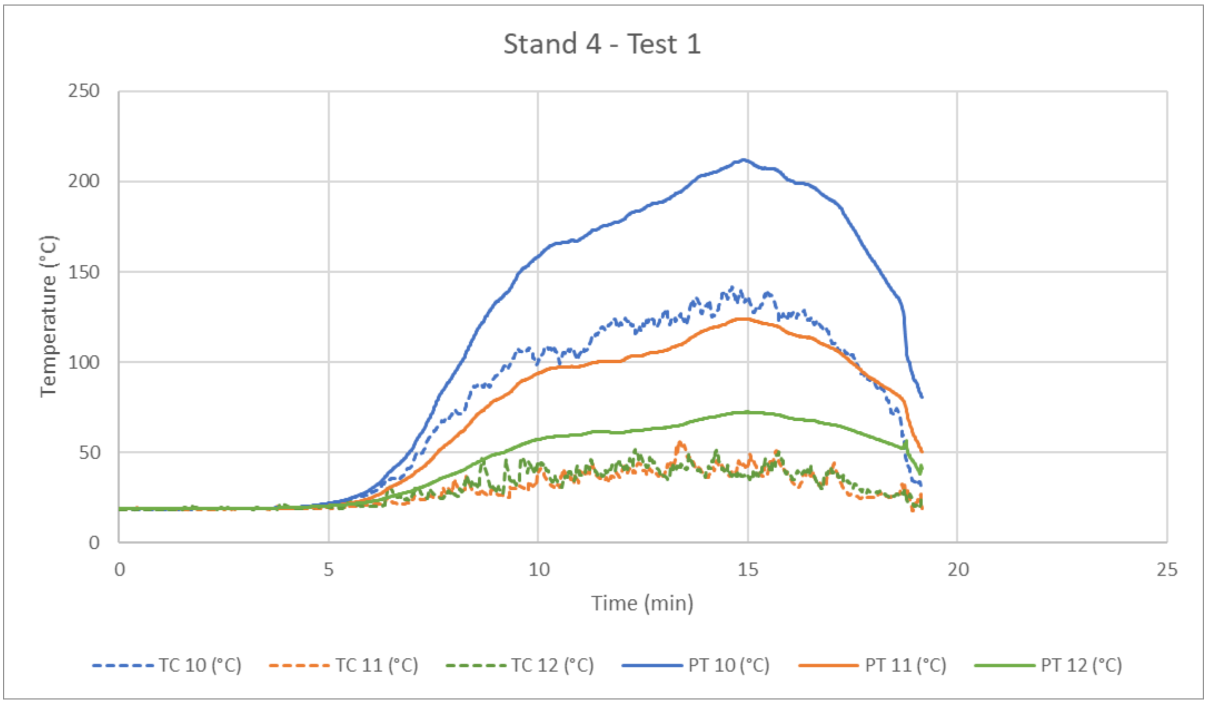

Figure 18. Temperature readings on Stand 4 (locations 10 to 12) – Test 1.

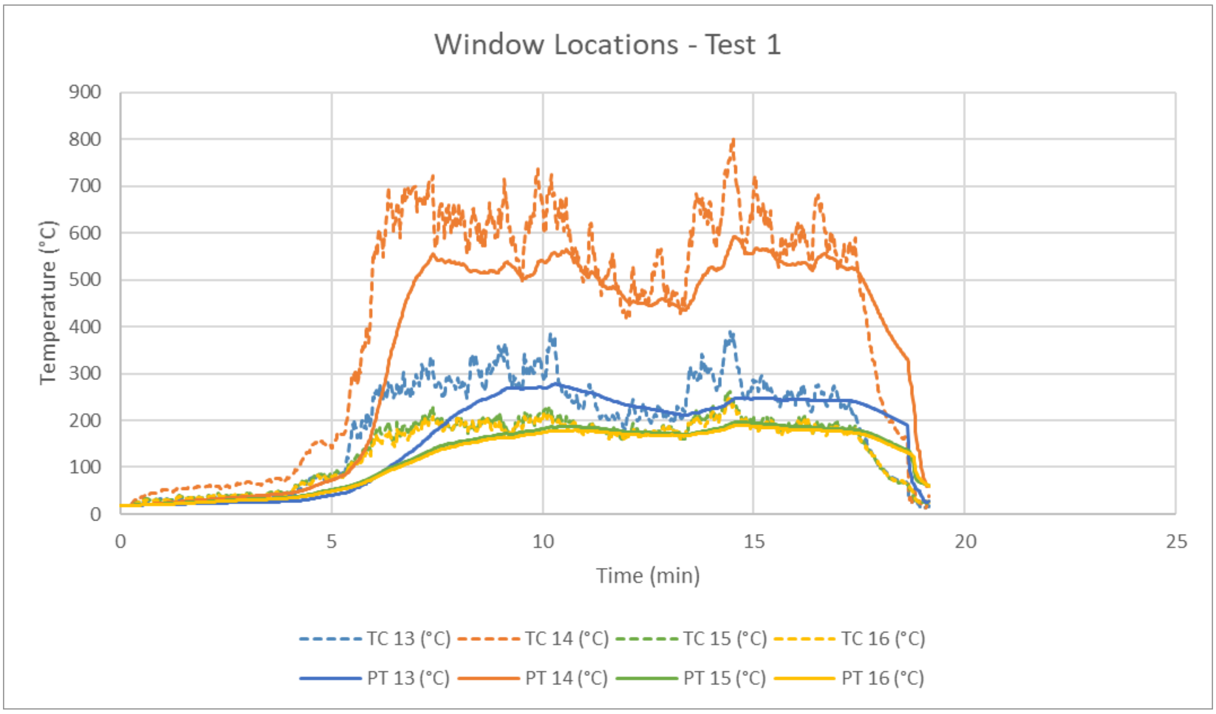

Figure 19. Temperature readings in window locations (locations 13 to 16) – Test 1.

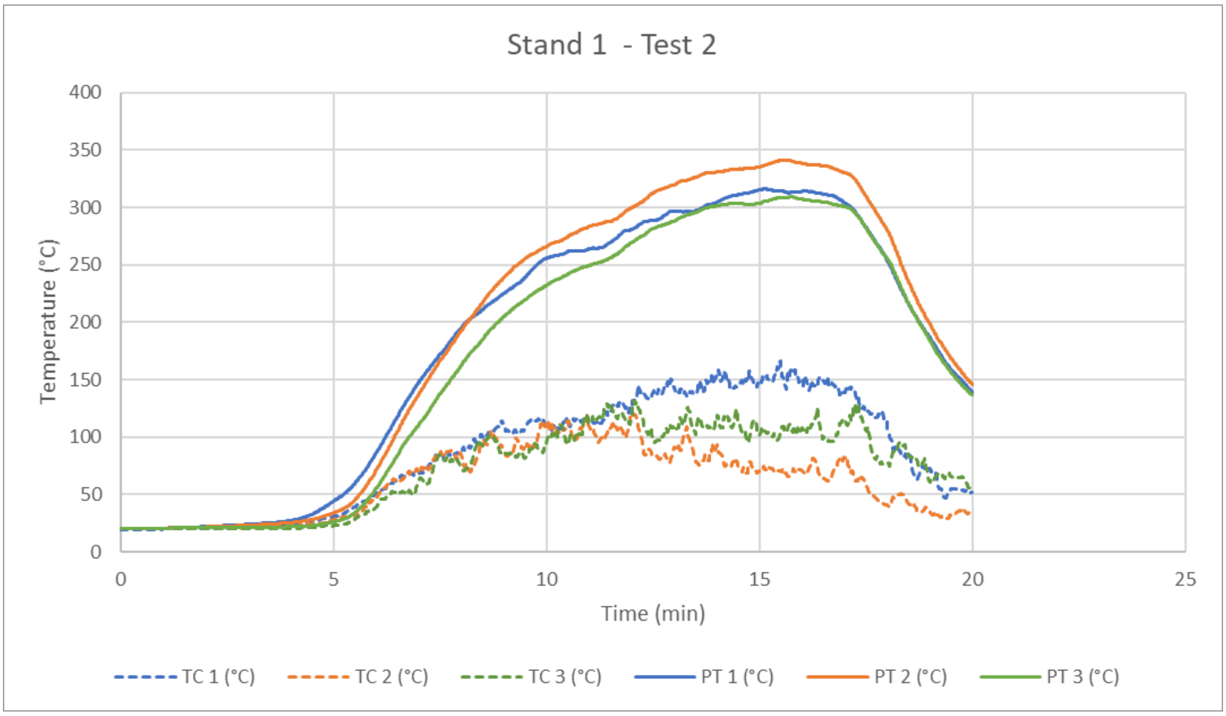

Figure 20. Temperature readings on Stand 1 (locations 1 to 3) – Test 2.

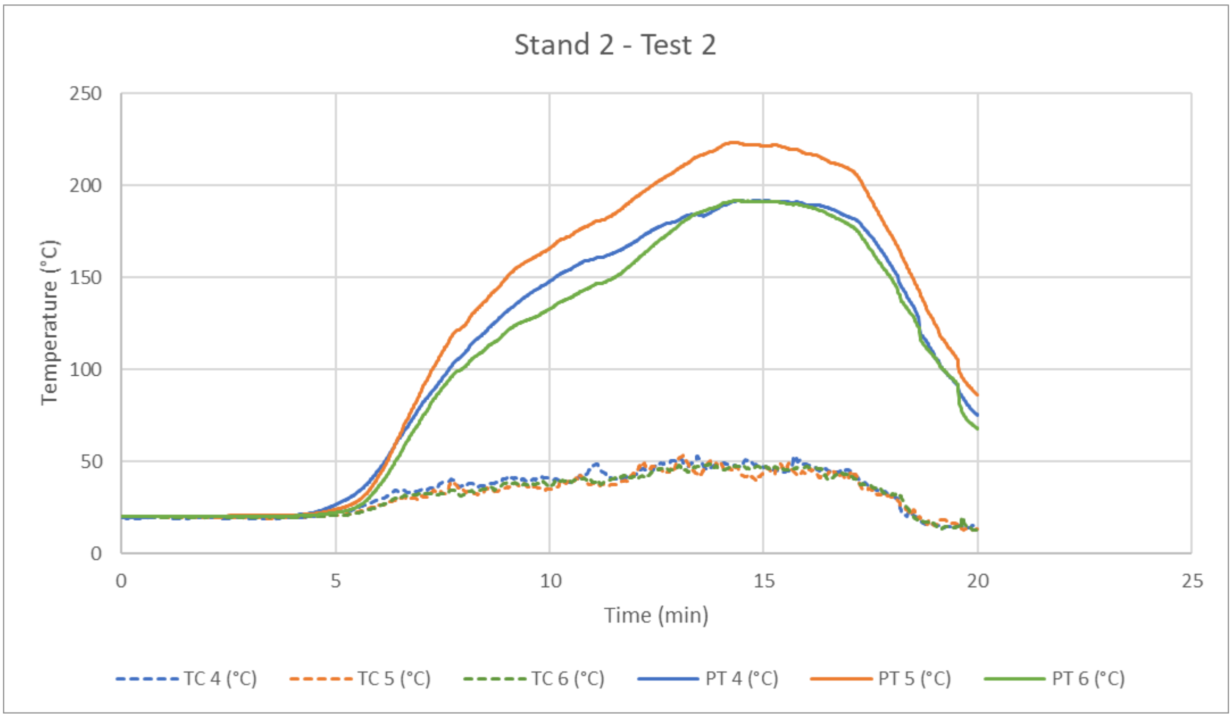

Figure 21. Temperature readings on Stand 2 (locations 4 to 7) – Test 2.

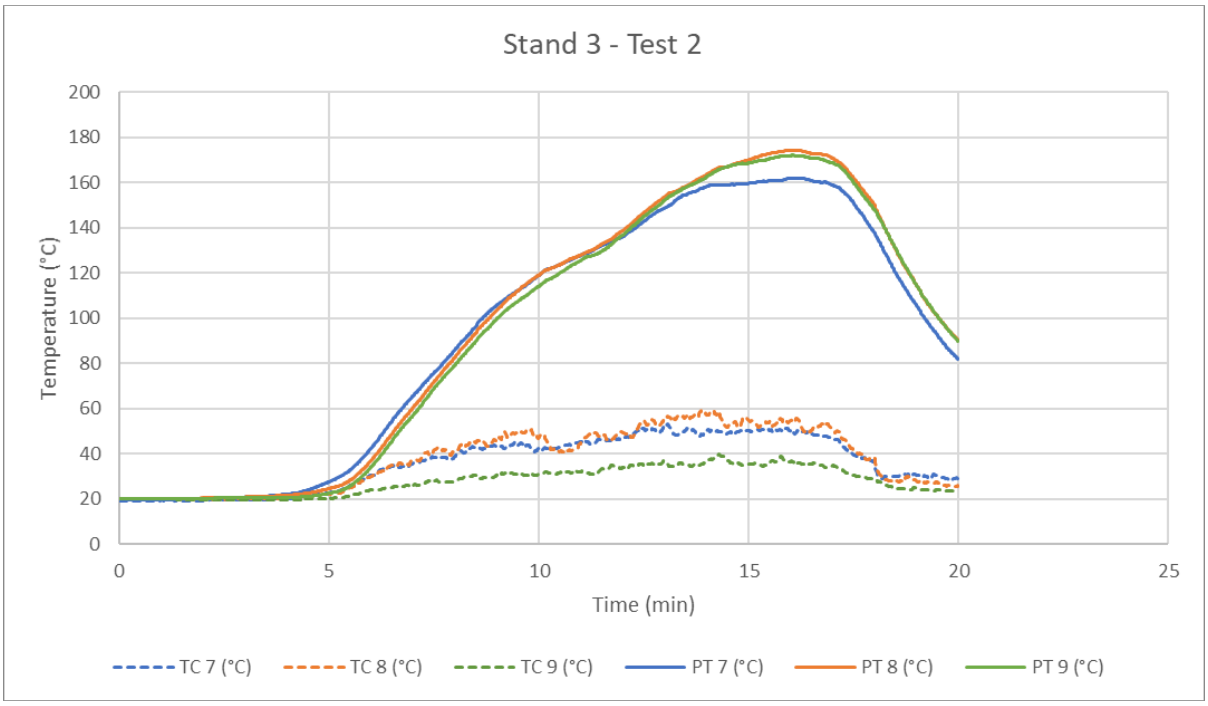

Figure 22. Temperature readings on Stand 3 (locations 7 to 9) – Test 2.

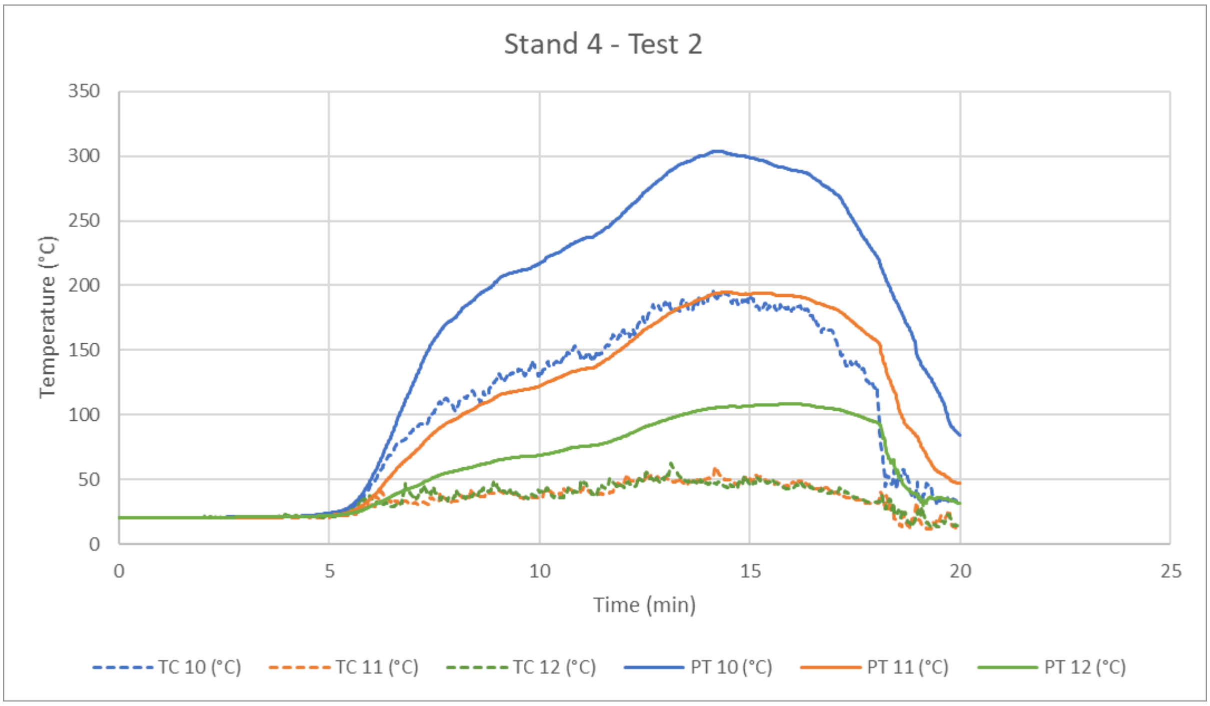

Figure 23. Temperature readings on Stand 4 (locations 10 to 12) – Test 2.

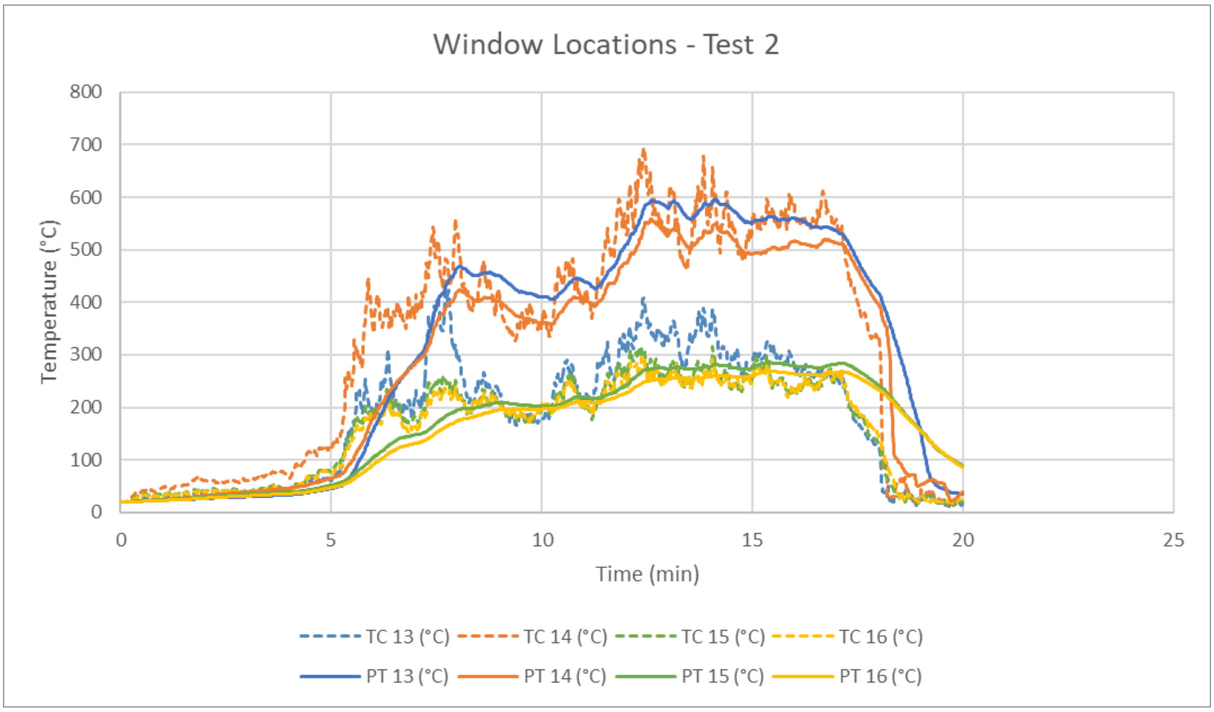

Figure 24. Temperature readings in window locations (locations 13 to 16) – Test 2.

11.1.2 Calculated Heat Fluxes

Figure 25 to Figure 29 show the calculated heat-flux histories for each of the measurement locations for Test 1 with Figure 30 to Figure 34 showing the same for Test 2. Figure 29 and Figure 34 also include the measurements from the Heat Flux Meters positioned in the lower window for Test 1 and Test 2, respectively. The incident heat fluxes have been calculated over a 10s period.

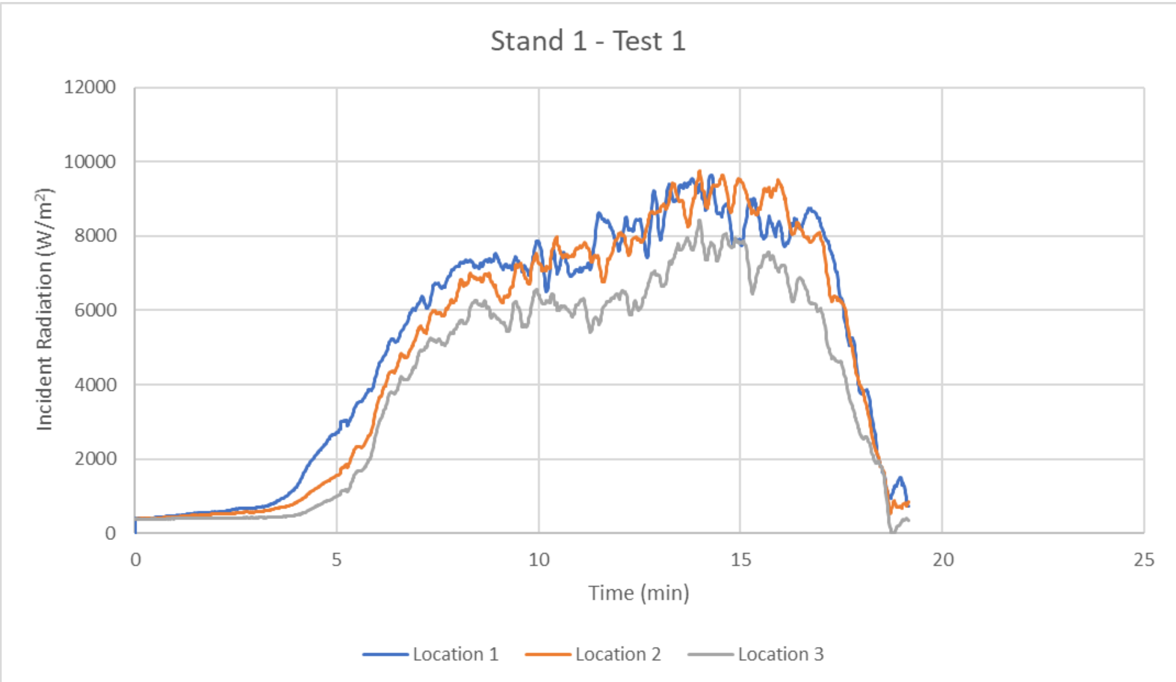

Figure 25. Calculated heat fluxes for Stand 1 (locations 1 to 3) – Test 1.

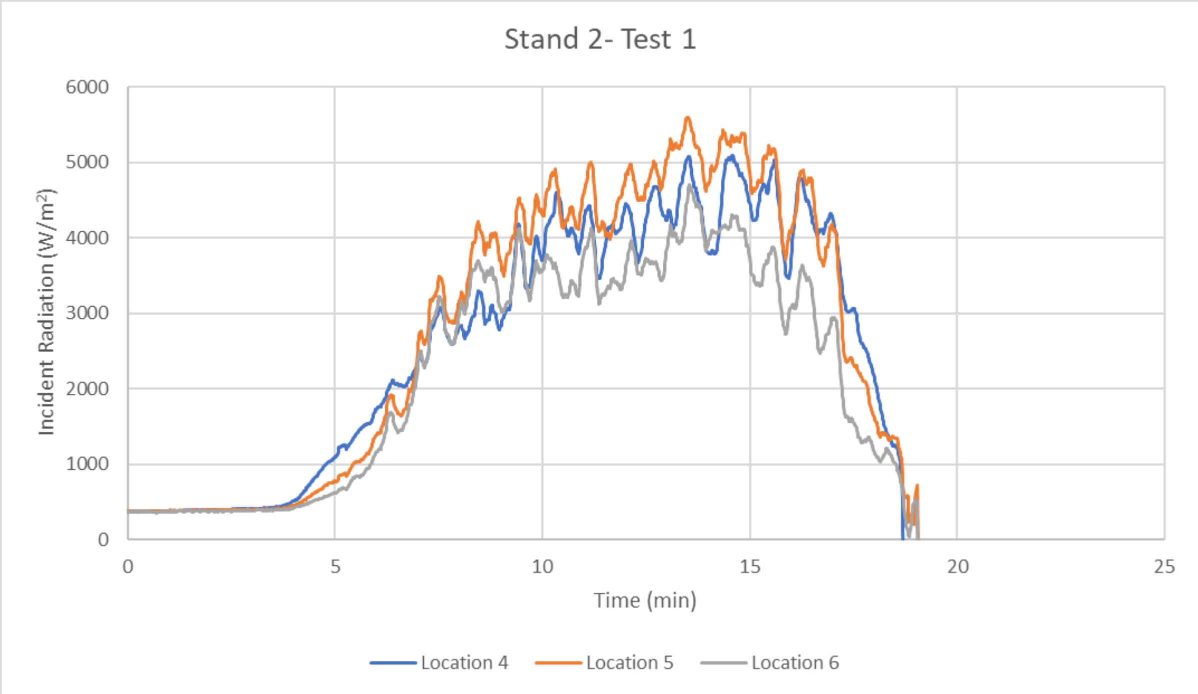

Figure 26. Calculated heat fluxes for Stand 1 (locations 4 to 6) – Test 1.

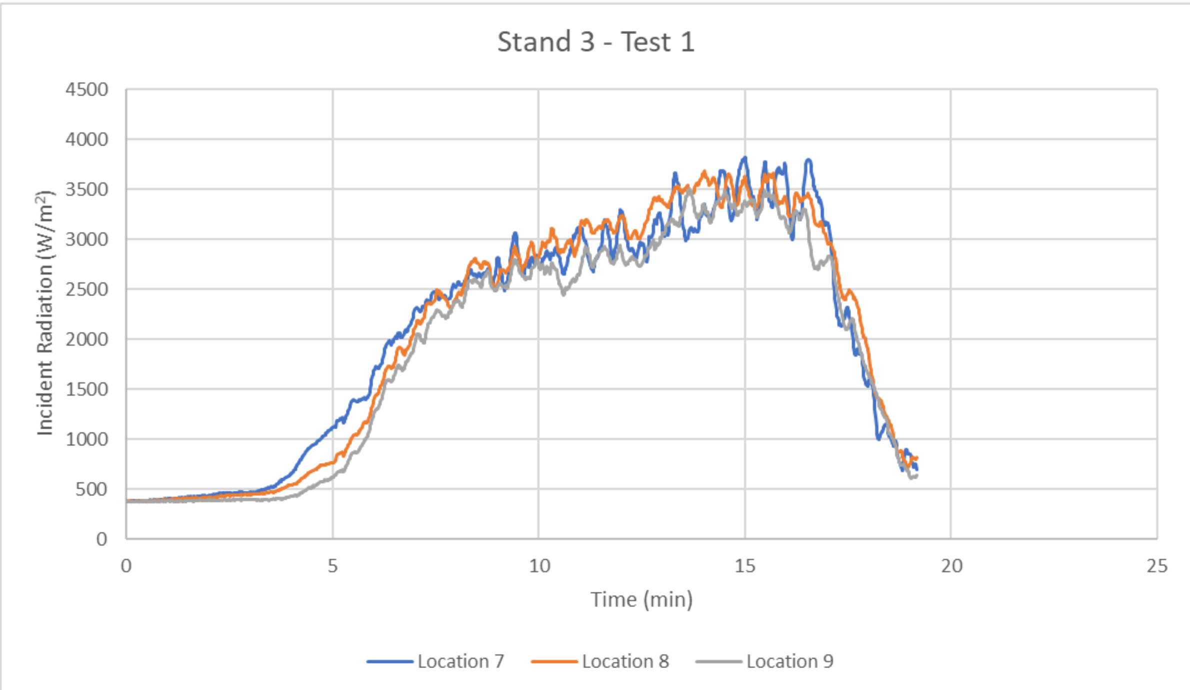

Figure 27. Calculated heat fluxes for Stand 3 (locations 7 to 9) – Test 1.

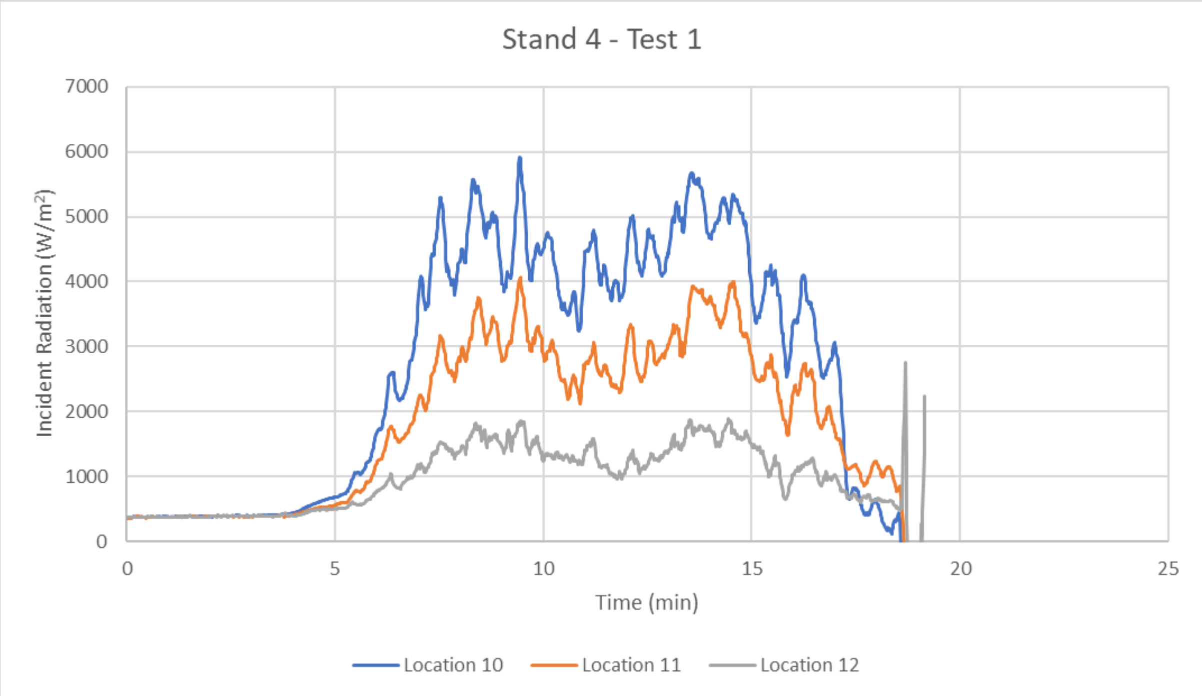

Figure 28. Calculated heat fluxes for Stand 4 (locations 10 to 12) – Test 1.

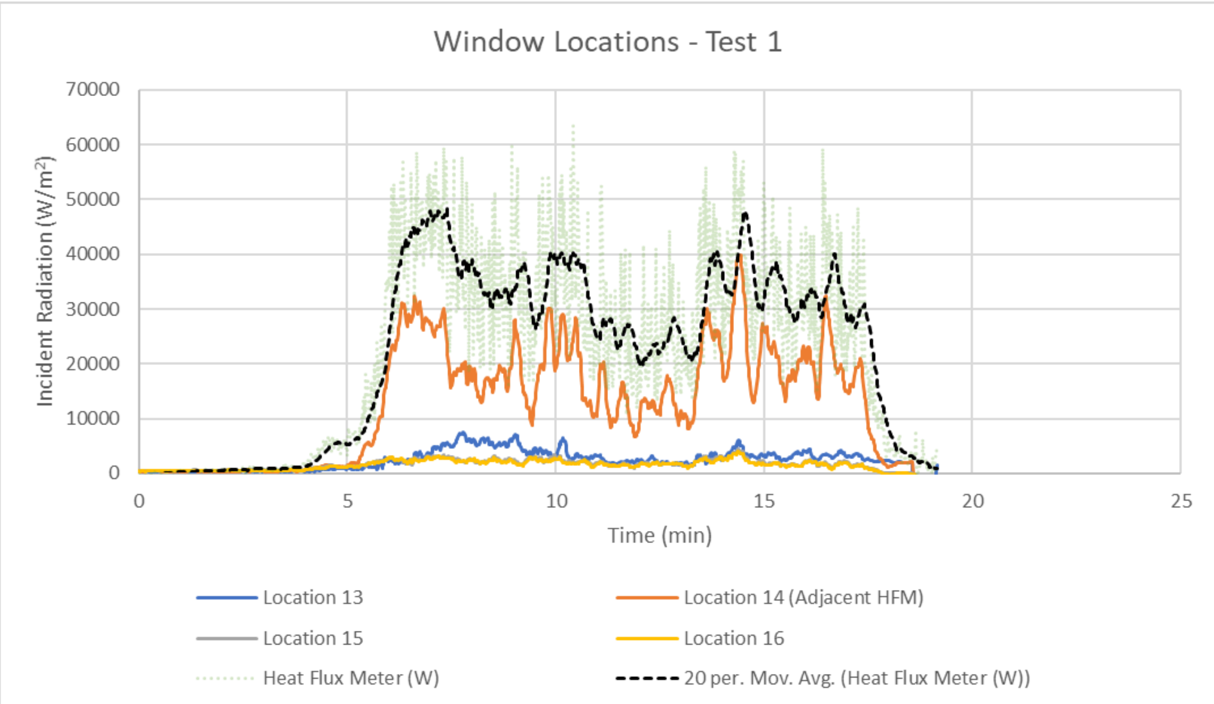

Figure 29. Calculated heat fluxes for window locations (locations 13 to 16 and the Heat Flux Meter) – Test 1.

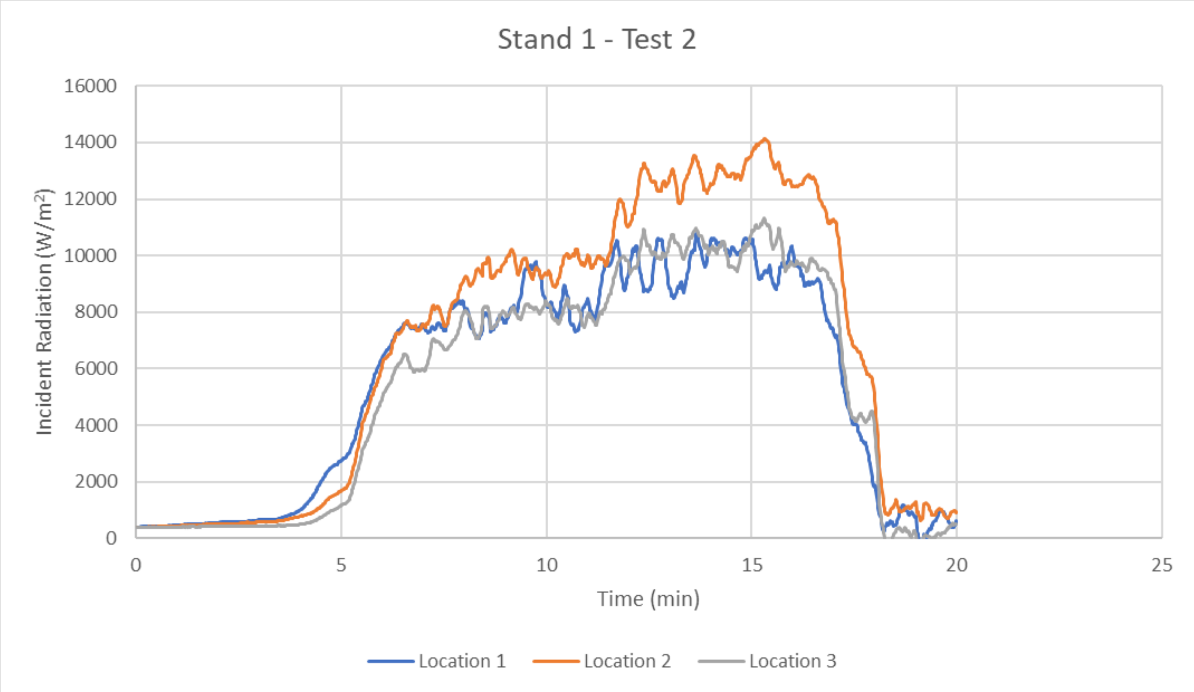

Figure 30. Calculated heat fluxes for Stand 1 (locations 1 to 3) – Test 2.

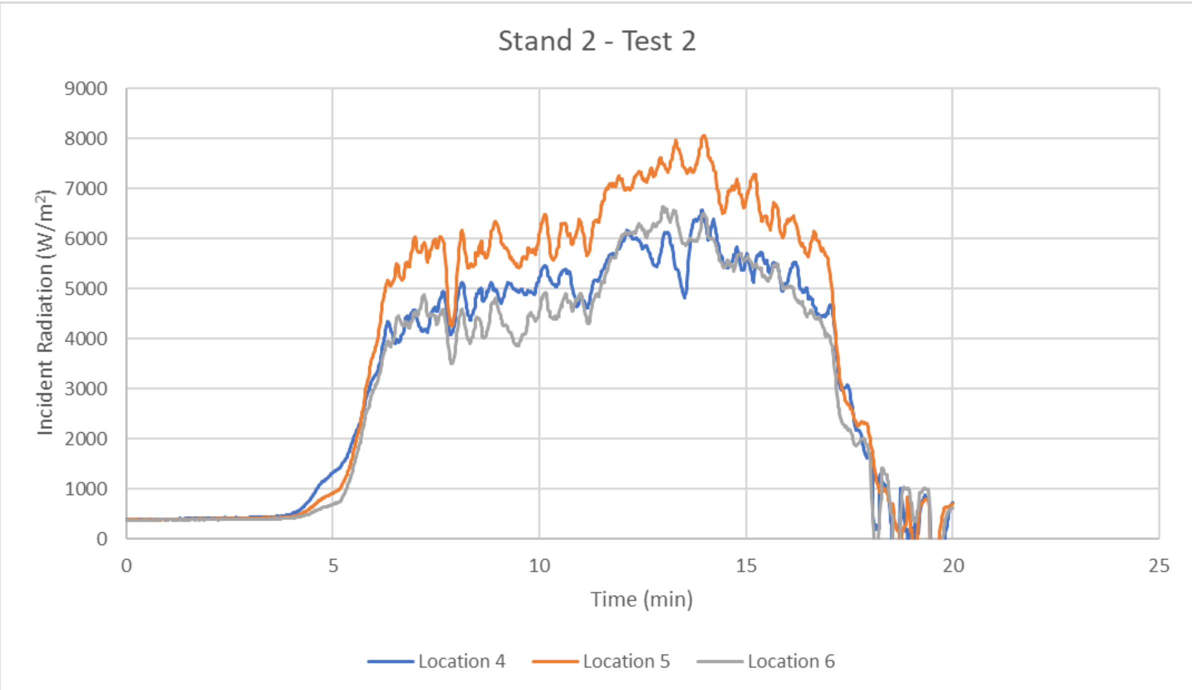

Figure 31. Calculated heat fluxes for Stand 1 (locations 4 to 6) – Test 2.

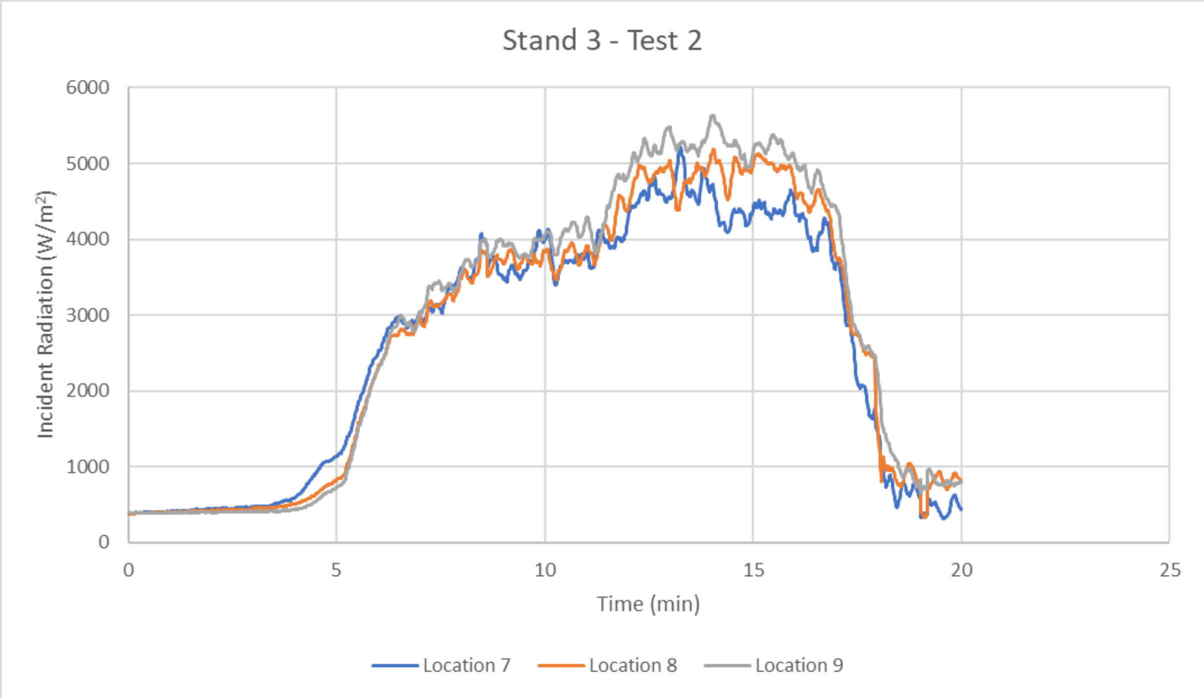

Figure 32. Calculated heat fluxes for Stand 3 (locations 7 to 9) – Test 2.

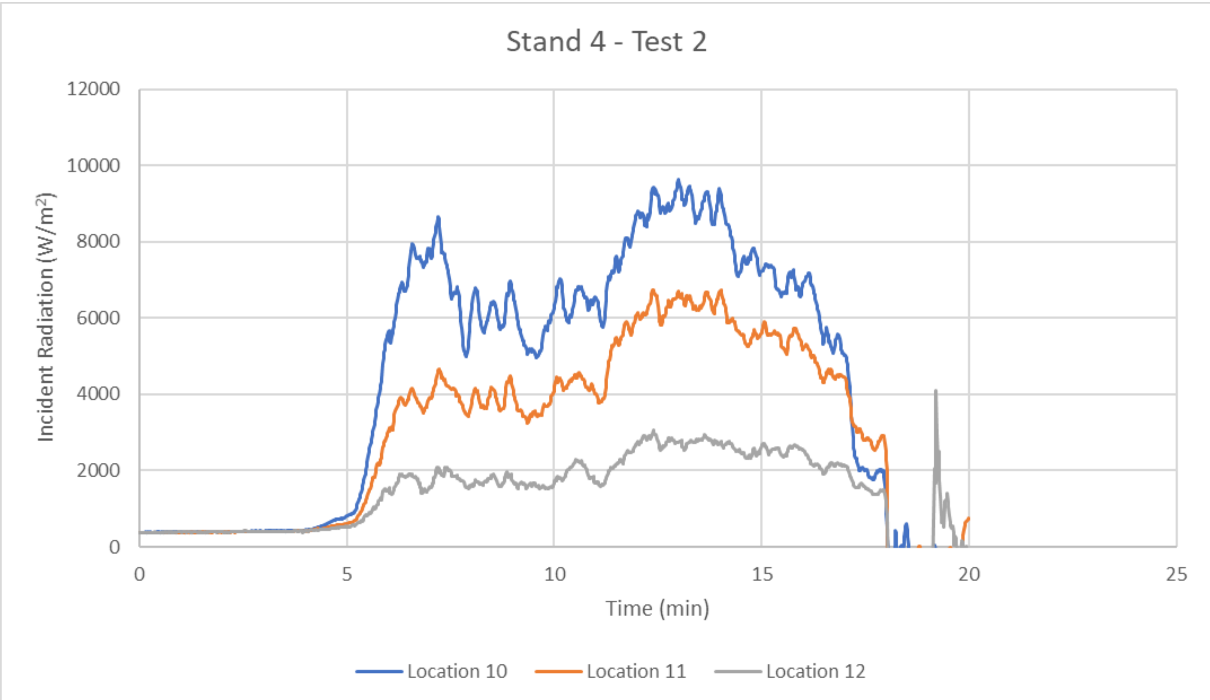

Figure 33. Calculated heat fluxes for Stand 4 (locations 10 to 12) – Test 2.

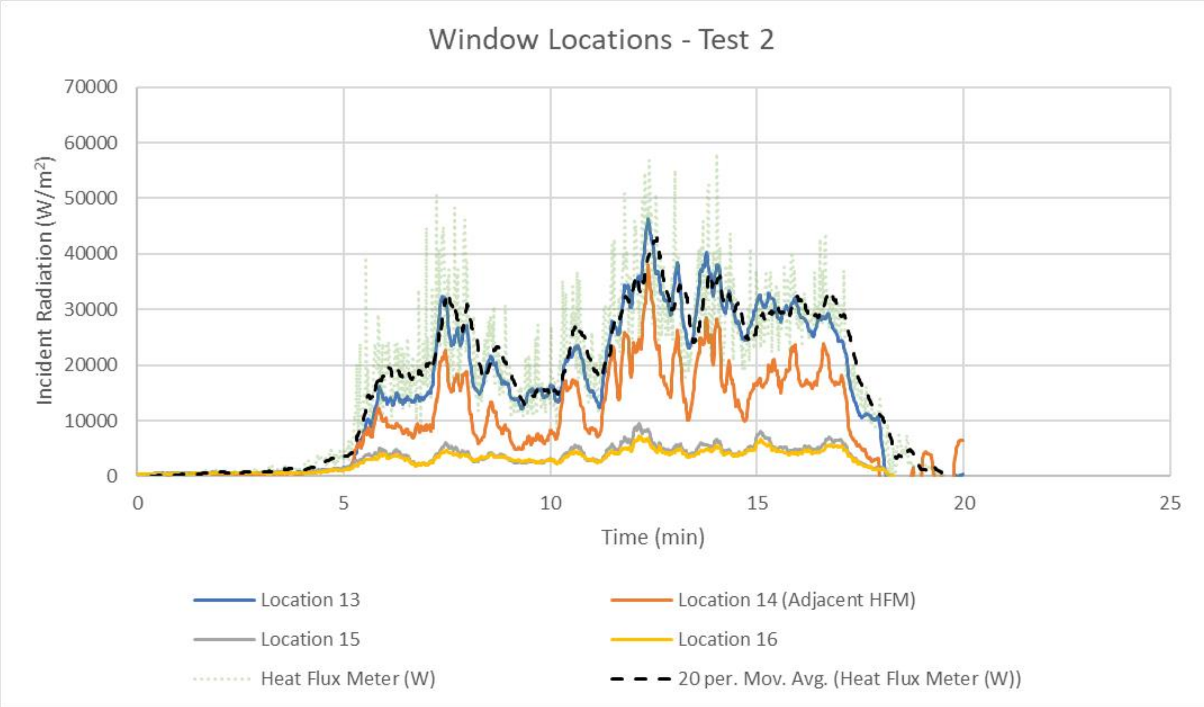

Figure 34. Calculated heat fluxes for window locations (locations 13 to 16 and the Heat Flux Meter) – Test 2.

11.2 ANNEX B – Full Experimental Results, Cone Calorimeter Ignition Tests

This annex contains the raw results from the cone calorimeter tests. Further details on the methodology for these tests and descriptions of the materials tested can be found in section 6.1.1 and 6.2.1.

Material 1 (hard glass fibre casing material) - Piloted Ignition			
Heat Flux (kW/m^2)	Time to ignition (s)		
	Sample 1	Sample 2	Sample 3
15	216	261	-
12	909	No ignition	671
10	No ignition	334	334
8	No ignition	No ignition	No ignition

Material 1 (hard glass fibre casing material) - Unpiloted Ignition			
Heat Flux (kW/m^2)	Time to ignition (s)		
	Sample 1	Sample 2	Sample 3
30	133	167	-
25	196	229	-
24	436	403	355
22	No ignition	No ignition	No ignition
20	No ignition	No ignition	-
15	No ignition	-	-

Material 3 (black plastic fabric) - Piloted Ignition			
Heat Flux (kW/m^2)	**Time to ignition (s)**		
	Sample 1	**Sample 2**	**Sample 3**
15	75	40	No ignition
12.5	No ignition	203	289
10	543	No ignition	No ignition
7.5	No ignition	No ignition	-

Material 3 (black plastic fabric) - Unpiloted Ignition			
Heat Flux (kW/m^2)	**Time to ignition (s)**		
	Sample 1	**Sample 2**	**Sample 3**
25	87	102	-
22.5	No ignition	114	No ignition
20	No ignition	No ignition	-
15	No ignition	No ignition	-

Material 4 (orange plastic fabric) - Piloted Ignition			
Heat Flux (kW/m^2)	**Time to ignition (s)**		
	Sample 1	**Sample 2**	**Sample 3**
15	94	No ignition	128
12.5	No ignition	41	No ignition
10	No ignition	No ignition	-

Material 4 (orange plastic fabric) - Unpiloted Ignition			
Heat Flux (kW/m^2)	**Time to ignition (s)**		
	Sample 1	**Sample 2**	**Sample 3**
30	37	-	-
27.5	49	23	-
25	No ignition	No ignition	-
22.5	No ignition	-	-
20	No ignition	No ignition	-
17.5	No ignition	No ignition	-
15	No ignition	No ignition	-

No ignition was achieved in Material 3 when tested up to 20 kW/m^2. However, significant degradation was observed in the materials at heat fluxes as low as 2.5 kW/m^2 as can be seen in Figure 35 to Figure 39.


Figure 35. Lifejacket material after exposure to 2.5kW/m².

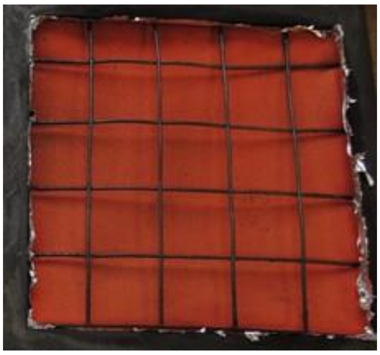


Figure 36. Lifejacket material after exposure to 5kW/m².


Figure 37. Lifejacket material after exposure to 7.5kW/m².

Figure 38. Lifejacket material after exposure to 10kW/m².

Figure 39. Lifejacket material after exposure to 20kW/m².