Fire Technology

Manufactured in The United States
https://doi.org/10.1007/s10694-021-01107-z

Assessing the Safety of Training Firefighters with the Minimum Requirements for Firefighter Garments

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Received: 28 May 2020/**Accepted:** 18 February 2021

Abstract. Every year, high numbers of firefighters are injured at fire incidents. A primary cause of moderate to severe injury can be linked to the protective garments worn by firefighters and understanding the limits of these protective garments is crucial for their safety. It would be substantially advantageous to firefighter safety if their available safe escape time is included in building design. To do this, the heat protective performance of firefighter garments needs to be translated into a tenable time. In this study, the minimum Thermal Protective Performance (TPP) rating of firefighter garments was investigated and found to compare well to known firefighter environments. This TPP rating was then used to further process the heat flux results from a CFD based fire model to determine an available safe escape time for firefighters. The probability of firefighters being injured was required in this study. It was used to assess the accuracy of the fire model in estimating the critical heat flux required to prevent a safe available escape time.

Keywords: Firefighter garments, TPP rating, Firefighter safety, Live fire training, CFD analysis

1. Introduction

Firefighters are injured at a higher rate when attending fire incidents than when attending non-fire incidents in the U.S. [1]. Amongst these injuries, those caused by exposure to fire products has seen an increase in recent years. Figure 1 shows that between 2014 and 2018, the linear trend for injuries caused by exposure to fire products positively increased while all other causes of injury negatively increased [1–5]. Exposure to fire products include exposure to heat, smoke and other gases produced during fires [6]. Firefighters commonly protect themselves from these fire products with their protective garments and self-contained breathing apparatus (SCBA) which is complete with a facepiece. The protection they provide may, however, be limited with significant heat exposure [7].

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Published online: 23 March 2021

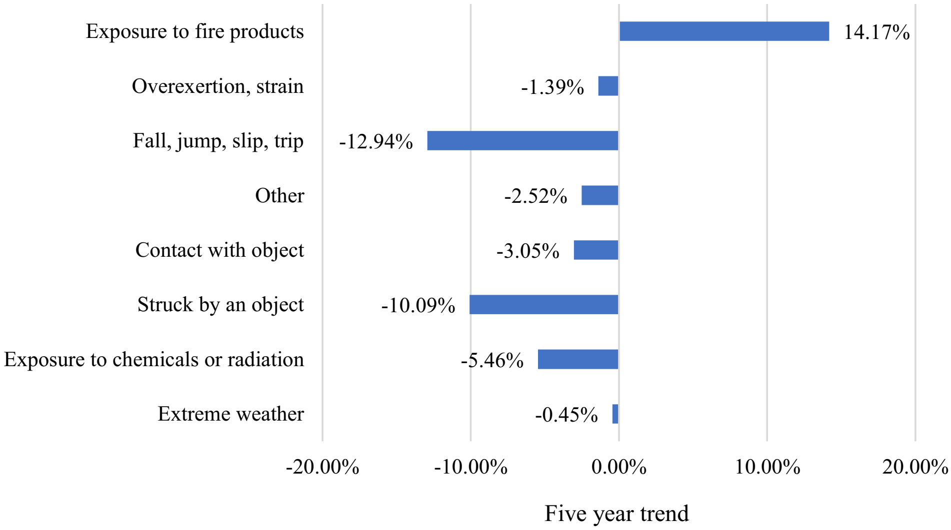

Figure 1. Five-year trend of fireground injuries by cause.

Burns are the second leading symptom of moderate and severe injuries on the fireground, with a frequency that is more than twice that of injuries caused by smoke inhalation [8–10]. Moderate to severe injuries are the greater concern for firefighters. They result in lost time and increase the danger of permanent disability [8].

Burn injuries also occur repeatedly during training [1–5]. Burn injuries during live fire training may result from various mistakes such as standing too close to the fire or the use of excessive fuel loads [11–13]. As well as on the fireground, death also occurs during training with one of the primary symptoms being burns [14–16]. These deaths have occurred during training in both acquired and purpose-built live fire training structures.

Burns that extend through the skin's epidermis and into the dermis are classified as second-degree burns [17]. Severe incapacitation is expected under such conditions that produce second-degree burns [18]. This occurs when tenable conditions have been lost [19]. Firefighter protective garments only provide a limited amount of protection from hot gasses, direct contact with hot surfaces, and thermal radiation [7]. They typically consist of three layers of fabric. Songe et al. [20] explains the following about these three layers.

1. The first layer is the outer shell. This helps to keep the integrity of the fabric assembly when exposed to flame, radiant heat, and hot surfaces. It also has a high mechanical strength structure to resist tears and punctures.
2. The middle layer is a moisture barrier. It prevents the transmission of hot liquids, but it may also allow sweat vapour to escape from the firefighter's body.

3. The last layer is the inner layer which is in contact with the firefighter's body. It raises the overall thermal insulation of the fabric assembly because it traps dead air, further insulating the firefighter from heat.

The effectiveness of the garment in protecting against heat flux exposure may become affected when wet [21, 22]. The added moisture content to the garments may be due to the sweating of the firefighter or from water spray splash back during firefighting operations [7, 23].

For protection against high heat flux exposure, NFPA 1971 specifies a Thermal Protective Performance (TPP) rating of 35 for firefighter garments comprising of these three fabric layers [24]. TPP measures the thermal insulation provided by clothing until the exposed heat flux results in a second-degree burn and is calculated as shown in Eq. 1 [24].

$$TPP_{rating;value} = F \times T \tag{1}$$

where F is the exposure energy heat flux measured in cal/cm^2.s, and T is the time to burn measured in seconds (1 cal/cm^2.s $\approx$ 41.87 kW/m^2).

Besides using the TPP rating, there are two alternatives considered when calculating the time to second-degree burns. They are the Thermal Dose Unit (TDU) method or by use of the Protective Clothing Performance Simulator [25].

The TDU method uses an equation similar to Eq. 1 except that the heat flux has an exponent of 4/3 [26]. By using the work of Su et al. [27], it was found that the results from the TDU method had a higher standard deviation than the results from the TPP rating. This is shown in Tables 1 and 2. The study by Su et al. [27] found the time taken to form second degree-burns for three different fire protective fabrics when exposed to a heat flux of 8.5, 30, and 84 kW/m^2. This range in heat flux is important. The TPP rating used in NFPA 1971 is calculated from a heat flux of 84 kW/m^2 [24] whereas the heat flux expected for tenable firefighter conditions is in the 8.5 kW/m^2 region [28, 29]. This allows for both the TDU and TPP rating to be calculated, and for their variance in results to be compared for low to high heat flux. It shows in Tables 1 and 2 that the TPP rating is more consistent across a wide range of heat fluxes. The term "spacer" in Tables 1 and 2, refers to an air gap used in the test and the term "planar" refers to the configuration of the test used by Su et al. [27].

The next alternative method for predicting burn injury in firefighters is the use of the Protective Clothing Performance Simulator [25]. This software tool has been developed for predicting the effectiveness of firefighter garments in protecting the skin from burn injury. However, it was unfortunately not available at the time of this study due to export control regulations.

The firefighter working conditions that have been documented by others could be individually used to determine tenable conditions for firefighters [28–32]. They however vary substantially between different sources. For example, Foster and Roberts [30] specifies 25 min for a 1 kW/m^2 heat flux exposure and Coletta et al. [31] specifies 5 min to 60 min for a 1.26 kW/m^2 heat flux exposure. Both sources

Table 1
TPP Rating and TDU Comparison Using the no Spacer—Planar Data

Time (s)	Heat flux (kW/m^2)	Heat flux (cal/cm^2.s)	TPP rating (cal/cm^2)	TDU rating (cal/cm^2)	TPP SD (cal/cm^2)	TDU SD (cal/cm^2)
*Fabric A*1						
36.0	8.5	0.20	7.31	4.30	0.39	1.62
9.0	30	0.72	6.45	5.77		
3.3	84	2.01	6.52	8.22		
*Fabric A*2						
40.0	8.5	0.20	8.12	4.77	0.45	1.78
11.5	30	0.72	8.24	7.37		
3.6	84	2.01	7.22	9.11		
*Fabric A*3						
35.0	8.5	0.20	7.11	4.18	0.45	1.40
9.0	30	0.72	6.45	5.77		
3.0	84	2.01	6.02	7.59		

Table 2
TPP Rating and TDU Comparison Using the Spacer—Planar Data

Time (s)	Heat flux (kW/m^2)	Heat flux (cal/cm^2.s)	TPP rating (cal/cm^2)	TDU rating (cal/cm^2)	TPP SD (cal/cm^2)	TDU SD (cal/cm^2)
*Fabric A*1						
71.0	8.5	0.20	14.41	8.47	1.06	3.49
16.5	30	0.72	11.82	10.58		
6.6	84	2.01	13.24	16.70		
*Fabric A*2						
71.0	8.5	0.20	14.41	8.47	0.89	4.10
17.5	30	0.72	12.54	11.22		
7.2	84	2.01	14.45	18.22		
*Fabric A*3						
67.0	8.5	0.20	13.60	7.99	0.74	3.54
16.5	30	0.72	11.82	10.58		
6.5	84	2.01	13.04	16.45		

specify a heat flux of approximately 1 kW/m^2, however their allowable exposure time is vastly different.

In an effort to reduce injury and death of working firefighters, the National Fallen Firefighters Foundation consider it appropriate to use available technologies when it can result in increased health and safety [33]. The heat flux required for untenable firefighter conditions is the critical heat flux. The ability to calculate the location and duration of tenable spaces that are safe from critical heat fluxes allows for existing available technologies, such as fire models, to be used in determining safer working conditions for firefighters. This can be used to determine areas that are untenable to firefighters and their available safe escape time (ASET) for new and existing structures.

1.1. Present Study

The present study examines the minimum garment requirements for assessing the firefighter's protection from critical heat flux levels. The purpose is to use the garments minimum required TPP rating and then apply it to a real example to find the ASET of firefighters.

The ground floor of an acquired live fire training structure in Durban, South Africa, is used in this study (refer to Figs. 2 and 3). The study is not specifically addressing live fire training. Live fire training is used to simulate realistic fire scenarios that are encountered by firefighters [34]. Using the live fire training structure in this study provides a realistic scenario that firefighters are trained for.

The live fire training structure has been simulated using the CFD software, Fire Dynamics Simulator (FDS). It models thermal-driven fluid flow by numerically solving a form of the Navier stokes equations appropriate for thermally-driven, low Mach flow [35]. Figure 4 shows the ground floor modelled in FDS. For an in-depth review of FDS, the reader is directed to the FDS Technical Reference Guide [36]. FDS is used to calculate the heat flux used in this study.

The objectives for this study are as follows:

1. Compare the firefighter garments minimum TPP rating with known firefighter limits.
2. Prepare and demonstrate a method for calculating the TPP value from the FDS results.

2. Methodology

2.1. Selecting the Appropriate TPP Value

The term "TPP rating" refers to the rating that has been given to an item of clothing based on its performance in the TPP test. In this study, the term "TPP value" is also used. It too is calculated from Eq. 1 (refer to Introduction) but is used to define the heat flux exposure from the environment.

For flashover fires, NFPA 1971 specifies using half the garment's TPP rating when approximating the time at which second-degree burns occur [24]. This means that clothing that has the minimum required TPP rating of 35 can only be subjected to a heat flux for a specific time period that would result in a 17,5 TPP value.

Behnke [37] specifies doubling a garment's TPP rating for the anticipated heat flux exposure, which was proved at different heat flux levels. The doubling of the garment's TPP rating is described as a safety factor for preventing burns from stored heat in clothing and for any variation in the fabric spacing on the wearer [37].

Figure 2. Inside the live fire training structure, facing the front of the structure.

Figure 3. Inside the live fire training structure, facing the rear of the structure.

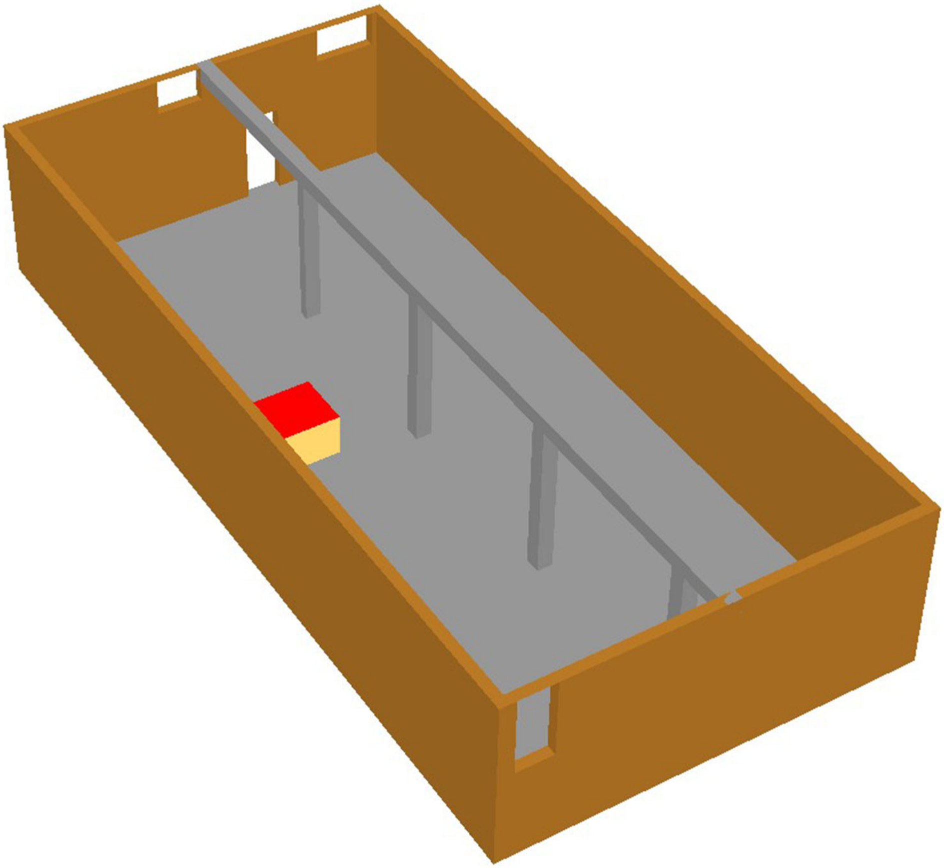

Figure 4. Ground floor of Durban's live fire training structure.

To determine the appropriate TPP value, a 17.5 and 35 TPP value is assessed. The simulation performed for this study is 1300 s long. The time to achieve a critical heat flux is assessed every 100 s into the simulation. The time remaining in the simulation is the exposure time. The critical heat flux can be calculated by using the exposure time and Eq. 1. Knowing the critical heat flux and exposure time allows for a comparison to be made with previously acknowledged firefighter conditions.

The critical heat flux calculated from a 20 s exposure and a 60 s exposure has also been included in the comparison. A 20 s exposure limit is typical of an emergency situation [31] and is similar to the situation being created in the NFPA 1971 TPP test [24]. For a 60 s exposure limit, firefighters would not be expected to perform search and rescue operations [29].

The known limits for firefighter heat flux exposure and time duration, have been specified by Abbott, Schulman [28], Foster, Roberts [30], Coletta et al. [31], Donnelly et al. [29] and FEMA/USFA [32]. This time limit is the time to pain and not to a second-degree burn. Peacock et al. [38] identified the time between pain and a second-degree burn for firefighter turnout coats of various TPP ratings. An average of 10–40 s between pain and second-degree burn was calculated from their loveseat fires and fully furnished room fires.

This additional time can be considered when determining the time for the firefighter to exit the burn room. Firefighters may exit by crawling, in which instance the crawl speed may range between 0.48 m/s and 2.4 m/s [39]. For a safe horizontal walking speed of 1.2 m/s [40], the exit time in this study is 15 s. This anticipated additional time between pain and second-degree burn has allowed for the firefighter to safely exit the burn room when the critical TPP value is reached and before receiving a second-degree burn.

In Tables 3 and 4, the marked cells show the known limits for firefighter heat flux exposure which compare with the 17.5 and 35 TPP values. It is clear that a 17.5 TPP value provides a more adequate comparison to tenable firefighter conditions and is appropriate for this study. The 20 s exposure shows good comparison with both the 35 TPP value and the 17.5 TPP value. However, Alarifi et al. [41] showed in their study of live fire training, firefighters could only with stand a 35 kW/m^2 heat flux for 20 s. This is only a good comparison for a 17.5 TPP value. It is noted that only Table 4 shows a favourable comparison with the permitted heat flux before the degradation of the SCBA facepiece occurs. Putorti et al. [42] studied the degradation of the facepiece subjected to various heat fluxes up to 15 kW/m^2. Their results show that the forming of bubbles and holes in the facepiece will require longer exposure times than that derived from a 17.5 TPP value with the same heat flux. This ensures the protection provided by SCBA and facepiece is complete when the 17.5 TPP value is used.

2.2. Design Fire

The fuel that is commonly used in the existing facility is wood. The combustion properties of wood have been well documented. It is a common choice of fuel for live fire training facilities and is considered to be a requirement [43]. Firefighter deaths have occurred in the past when various additional fuels have been negligently added to the fire during training and should not be allowed [44]. Wood pallets are proposed and are the fuel that is used in this research.

The pallet fire tests documented by Krasner [45] provide a comprehensive pallet stack height range. However, this document was not available for viewing at the time of this study. The information from Krasner has been compiled according to the cited information by Lee [46]. The pallet tests consisted of a single stack of pallets. The individual pallet size was 1.22 m × 1.22 m × 0.14 m and had a mass of 31.75 kg. Table 5 details the mass loss rates from the pallet fire tests.

This information then allows the peak HRR to be calculated from Eq. 2

$$HRR = \Delta h_c \times MLR \tag{2}$$

Table 3
Comparison of Firefighter Tenable Limits and a 35 TPP Value

TPP 35						
Exposure time (s)	Critical heat flux (kW/m^2)	Abbot	Foster	Coletta	NIST	USFA/FEMA
1300	1.13			X		
1200	1.22	X		X		X
1100	1.33	X		X		X
1000	1.47	X		X		X
900	1.63	X		X	X	X
800	1.83			X	X	X
700	2.09			X		X
600	2.44		X	X		X
500	2.93		X	X		X
400	3.66			X		X
300	4.88	X		X	X	X
200	7.33	X		X	X	X
100	14.65					X
60	24.42				X	X
20	73.27	X		X	X	X

Table 4
Comparison of Firefighter Tenable Limits and a 17.5 TPP Value

TPP 17.5						
Exposure time (s)	Critical heat flux (kW/m^2)	Abbot	Foster	Coletta	NIST	USFA/FEMA
1300	0.56		X	X	X	
1200	0.61	X	X	X	X	X
1100	0.67	X	X	X	X	X
1000	0.73	X	X	X	X	X
900	0.81	X	X	X	X	X
800	0.92	X	X	X	X	X
700	1.05	X		X	X	X
600	1.22	X	X	X	X	X
500	1.47	X	X	X	X	X
400	1.83		X	X	X	X
300	2.44	X	X	X	X	X
200	3.66	X		X	X	X
100	7.33	X		X	X	X
60	12.21	X			X	X
20	36.63	X		X	X	X

Table 5
Mass Loss Rate for Pallet Fires

Test #	# Pallets	Mass loss rate (kg/s)	
1	2.00	0.06	0.07 (Average)
2	2.00	0.08	
3	3.00	0.14	
4	5.00	0.20	0.21 (Average)
5	5.00	0.22	
6	7.00	0.26	
7	9.00	0.33	
8	11.00	0.42	

where h_c is the effective heat of combustion (kJ/kg) and *MLR* is the mass loss rate (kg/s) [47]. Heskestad, Delichatsios [48] specified using 12.5 MJ/kg as an actual heat of combustion for wood pallets. The moisture content of wood has been considered in the specified actual heat of combustion [49].

A typical HRR curve is determined from known HRR curves for pallet fires. Averill et al. [50] documented the HRR curves generated from a single stack of pallets that ranged in height from 0.44 m to 0.88 m. The free burn pallet tests are of interest, as these peak HRR results compare well with those documented by Lee [46].

The peak heat release rate that would result in a ventilation-controlled fire is avoided here to limit the possibility of dangerous fire phenomena occurring [43]. A ventilation-controlled fire is identified when the allowable heat release rate deviates from the fuel's prescribed heat release rate [51]. The heat release rate that can be sustained in the compartment before the fire becomes ventilation controlled is determined by modelling a t-squared fire with an appropriate growth coefficient. The growth coefficient used is 0.1876 kW.s^{-2} [52], which is an ultra-fast growth time similar to the growth coefficient calculated from Averill et al. [50].

The allowable simulated HRR starts to deviate from the prescribed HRR between 3000 kW and 4000 kW as shown in Fig. 5. Using Table 5 and Eq. 2, a single stack of seven pallets provide a 3250 kW fire (refer to Fig. 6). A seven-pallet fire should therefore be used.

The remaining wood pallet fuel properties required for FDS is shown in Table 6.

2.3. Validation and Grid Sensitivity

A validation range is created from the various non-dimensional parameters of multiple test series. The model's own non-dimensional parameters must be within this range. The non-dimensional parameters are separated into experimental parameters and numerical parameters. The test series and calculation method of the non-dimensional parameters are found in the FDS Validation Guide [55]. A test series was excluded if the test was conducted out in the open and the heat

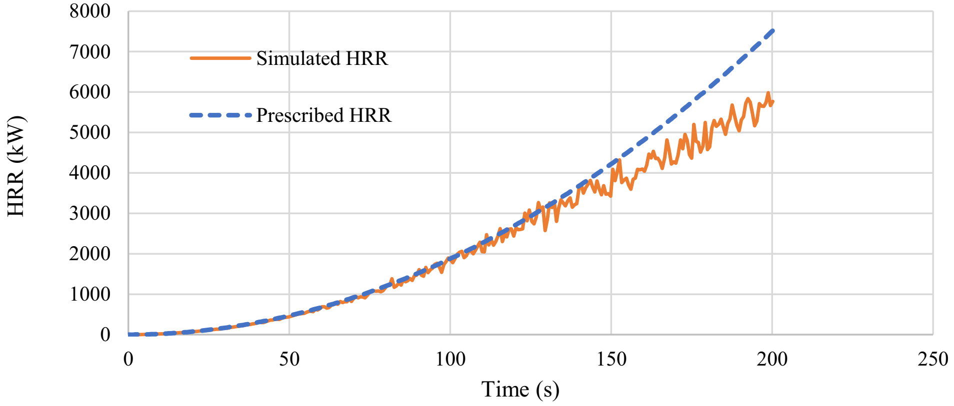

Figure 5. Ultra-fast fire comparison between simulated HRR and prescribed HRR.

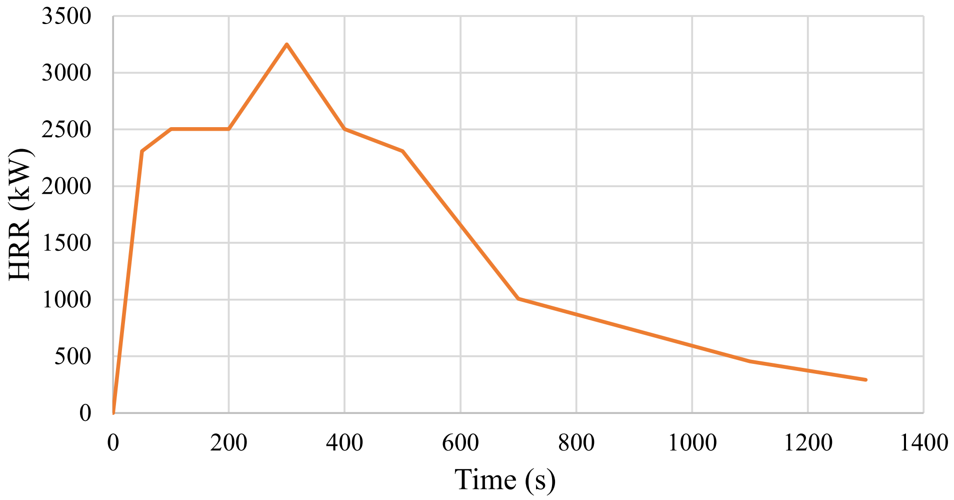

Figure 6. HRR for a single stack of seven pallets.

Table 6
Fuel Properties

Fuel properties		References
Chemical formula (pine wood)	$CH_{1.7}O_{0.83}$	[53]
CO yield	0.005	[54]
Soot yield	0.015	[54]

Table 7
Model Validation Range for Experimental Parameters

Description	Symbol	Validation range Min	Max	Calculated quantity
Fire Froude number	Q^*	0.2	24	1.4
Flame height relative to ceiling height	L_f/H_c	0.1	1.7	1.2
Global equivalence ratio	ø	0	5.9	0.4
Compartment aspect ratio	W/H_c	0.1	2.3	2.3
	L/H_c	0.2	43	4.9
Relative distance along the ceiling	r_{cj}/H_c	0	6	1.1
Relative distance from the fire	r_{rad}/D	0.3	5.7	5.5

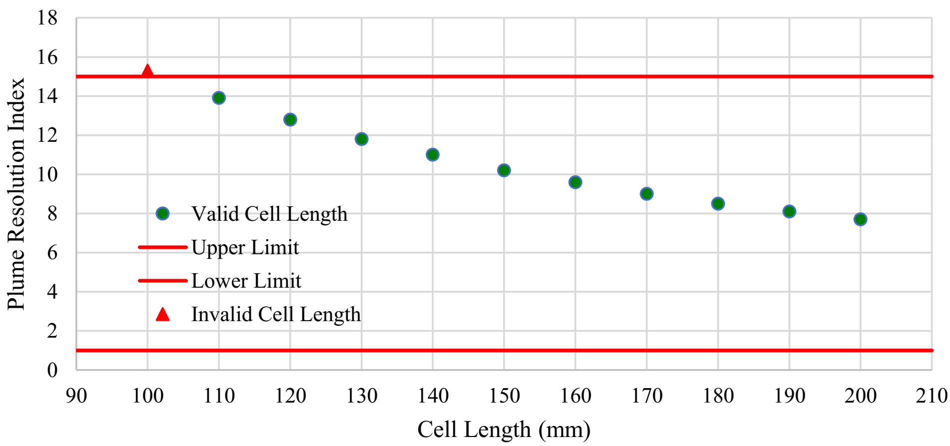

Figure 7. Plume resolution index vs cell length.

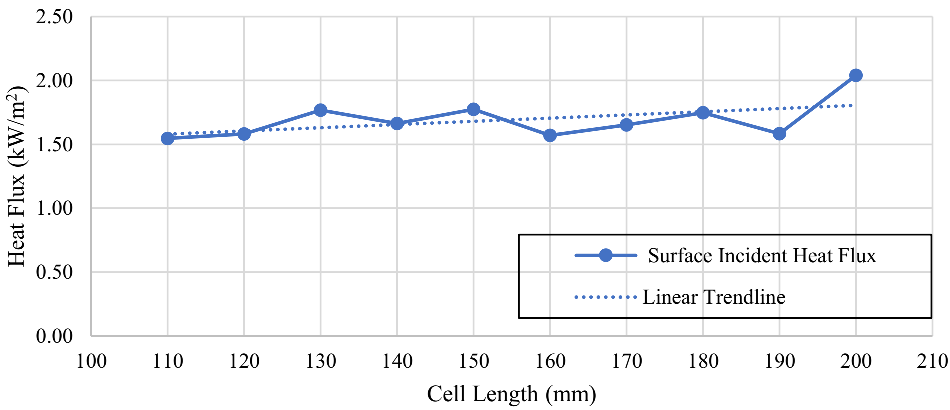

Figure 8. Heat flux at wall surface.

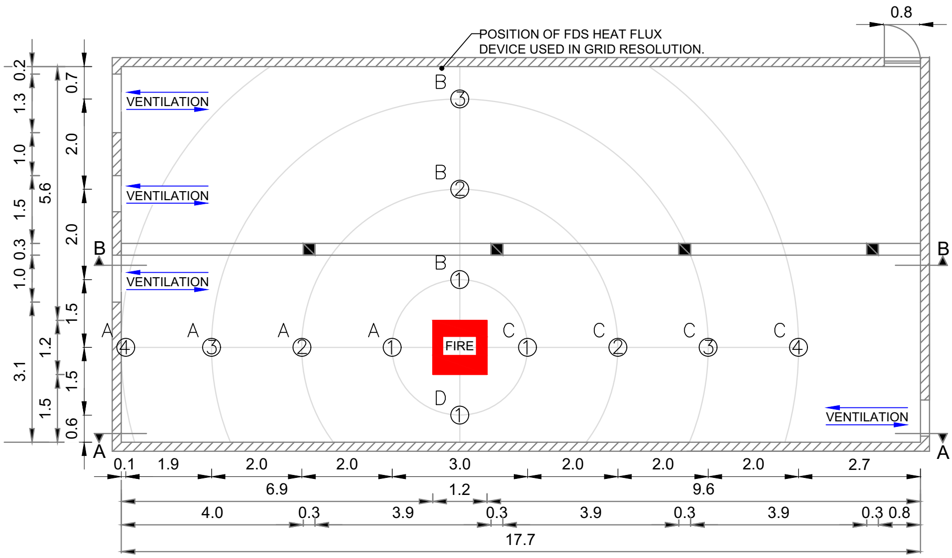

Figure 9. Position of FDS heat flux measuring devices as positioned in the simulation on the ground floor.

release rate used was overly excessive when compared to that used in this study. This resulted in 19 out of 36 test series being selected to create the validation range. The model was found to be within the validation range for all non-dimensional parameters as shown in Table 7.

A grid sensitivity study is performed for the quantity of interest which in this study is the heat flux. It is possible for a coarse grid to estimate results that are more accurate than a fine grid [56]. Therefore, a series of cell sizes are selected that result in a Plume Resolution Index being within validation range. This compares well with the grid cell sizes used in the simulations that validated the software. There are 10 different cell lengths selected that fit within the validation range as shown in Fig. 7.

Figure 8 presents the FDS heat flux results calculated near the fire's peak HRR at 250 s. The FDS heat flux device is positioned on the structure's back wall, 1.5 m above the floor (refer to Fig. 9). A trendline is drawn on the graph. This helps to locate the true value as the trend is clarified with accumulating measurement points.

Based on the results, the best grid size to be used is 110 mm x 110 mm x 110 mm. At this cell length, the heat flux is less dependent on the cell length.

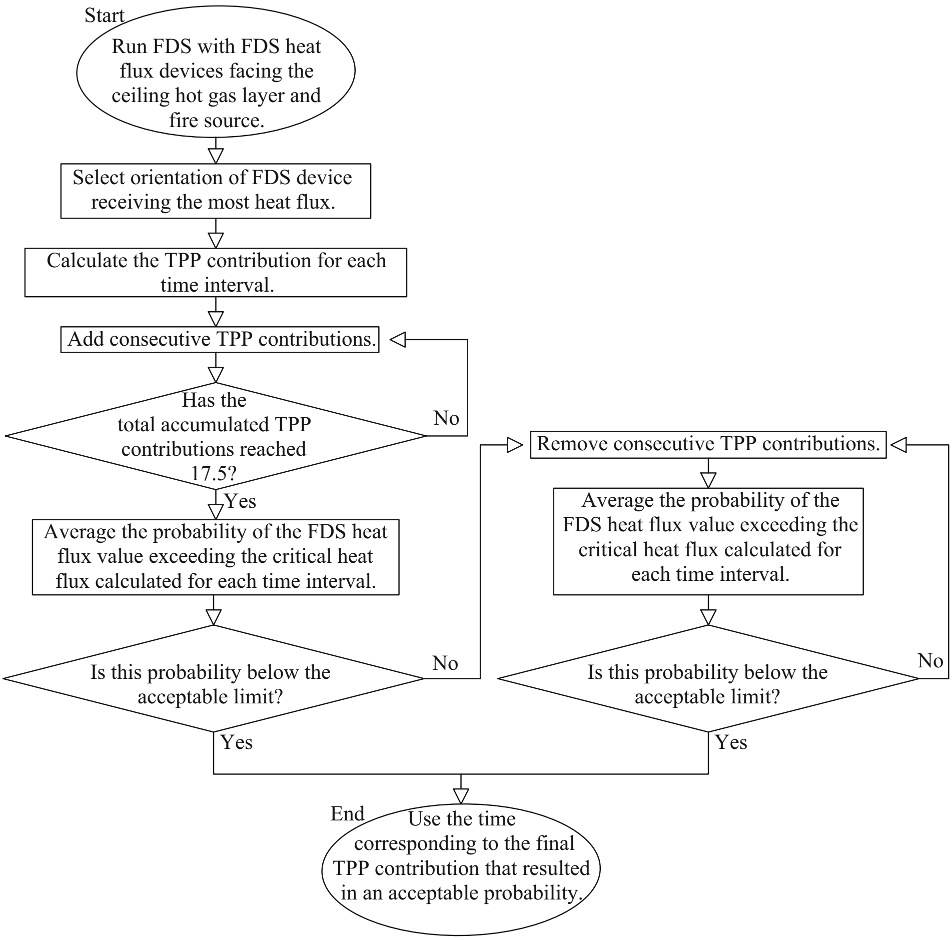

Figure 10. Results decision tree.

Table 8
Average Horizontal and Vertical Heat Flux Calculated at 1.5 m Above Floor Level on the Ground Floor

Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Location A1 (kW/m^2)		Location A2 (kW/m^2)		Location A3 (kW/m^2)	
10.007	7.808	**3.176**	2.814	1.313	**1.600**
Location A4 (kW/m^2)		Location B1 (kW/m^2)		Location B2 (kW/m^2)	
0.920	**1.010**	**9.295**	6.673	**2.709**	1.755
Location B3 (kW/m^2)		Location C1 (kW/m^2)		Location C2 (kW/m^2)	
0.932	0.794	**7.781**	4.366	**2.097**	1.573
Location C3 (kW/m^2)		Location C4 (kW/m^2)		Location D1 (kW/m^2)	
0.816	**1.047**	0.575	**0.906**	**8.684**	5.465

Table 9
Extract of Spreadsheet Used to Process FDS Results

A	B	C	D	E	F
s	kW/m^2	$cal/cm^2.s$	TPP contribution per time interval	Accumulated TPP (0 s)	Probability (0 s)
Time	RHFG A1	RHFG A1	RHFG A1	RHFG A1	
0.000	0.000	0.000	0.000	0.000	
1.353	0.053	0.001	0.002	0.002	0.000%
2.615	0.768	0.018	0.023	0.025	0.000%
3.915	1.369	0.033	0.042	0.067	0.000%
5.203	2.232	0.053	0.069	0.136	0.000%
6.508	2.603	0.062	0.081	0.217	0.000%
7.806	3.188	0.076	0.099	0.316	0.000%
9.109	3.356	0.080	0.104	0.420	0.000%
10.406	4.200	0.100	0.130	0.551	0.024%
11.702	4.542	0.108	0.141	0.691	0.164%
13.010	4.738	0.113	0.148	0.839	0.393%
14.309	5.543	0.132	0.172	1.011	4.327%

3. Results

The ground floor consists of a single large compartment as shown in Fig. 9. The FDS heat flux devices are positioned around the fire and in a way that allows the heat flux to be calculated as it radiates toward the outer edges of the compartment. Following the procedure in Fig. 10, the heat flux calculated in the positions shown in Fig. 9 is used to calculate the safe available time.

There are both vertical upward-facing FDS heat flux devices and horizontal-facing FDS heat flux devices positioned at 1.5 m above the floor (refer to Fig. 9). This is to investigate where the majority of the heat flux is being received. The heat flux calculated for vertical and horizontal FDS devices has been averaged in order to identify which FDS device will be used to calculate the thermal protective performance of the firefighter's garments. The selected FDS devices are those that received the highest heat flux average. Table 8 provides this information. The cells highlighted in bold identify whether a vertical or horizontal facing FDS device calculated the highest average heat flux.

The calculated heat flux for the duration of the simulation is presented in Figs. 12, 13, 14 and 15. Table 9 is an extract of the spreadsheet used to process the results from the live fire training structure. Column A is the data collected from a FDS heat flux measuring device. This data is converted from kW/m^2 to $cal/cm^2/s$ as used in the TPP formula. For every time interval calculated between time readings in column A, a TPP contribution is calculated and presented in column D. This TPP contribution is then summed in column E, starting from 0 s. The time taken for the accumulated TPP to reach 17.5 is then recorded as shown in Table 10. This is the time that is allowed before the minimum 17.5 TPP value

Table 10
Location of Occupying Time After Ignition of the Fire

	Occupying time at location (s)					
Location entry time after ignition (s)	A1	A2	A3	A4	B1	B2
0	83.2	209.3	336.7	479.7	85.8	243.1
100	57.2	161.2	262.6	412.1	62.4	196.3
200	53.3	135.2	236.6	405.6	59.8	172.9
300	49.4	133.9	243.1	529.1	53.3	166.4
400	53.3	146.9	323.7	**899.6**	57.2	174.2
500	55.9	178.1	556.4	**799.5**	61.1	213.2
600	61.1	261.3	**699.4**	**699.4**	68.9	292.5
700	75.4	345.8	**599.3**	**599.3**	83.2	386.1
800	85.8	435.5	**499.2**	**499.2**	92.3	**499.2**
900	98.8	**399.1**	**399.1**	**399.1**	104.0	**399.1**
1000	122.2	**300.3**	**300.3**	**300.3**	124.8	**300.3**
1100	148.2	**200.2**	**200.2**	**200.2**	152.1	**200.2**
1200	**100.1**	**100.1**	**100.1**	**100.1**	**100.1**	**100.1**

	Occupying time at location (s)					
Location entry time after ignition (s)	B3	C1	C2	C3	C4	D1
0	560.3	81.9	270.4	492.7	570.7	76.7
100	505.7	70.2	253.5	442.0	522.6	62.4
200	516.1	74.1	256.1	460.2	577.2	66.3
300	625.3	70.2	260.0	555.1	715.0	61.1
400	**899.6**	75.4	287.3	774.8	**899.6**	67.6
500	**799.5**	81.9	341.9	**799.5**	**799.5**	72.8
600	**699.4**	85.8	405.6	**699.4**	**699.4**	76.7
700	**599.3**	102.7	479.7	**599.3**	**599.3**	92.3
800	**499.2**	110.5	**499.2**	**499.2**	**499.2**	98.8
900	**399.1**	120.9	**399.1**	**399.1**	**399.1**	109.2

Table 10 continued

Location entry time after ignition (s)	Occupying time at location (s)					
	B3	C1	C2	C3	C4	D1
1000	**300.3**	139.1	**300.3**	**300.3**	**300.3**	127.4
1100	**200.2**	165.1	**200.2**	**200.2**	**200.2**	149.5
1200	**100.1**	**100.1**	**100.1**	**100.1**	**100.1**	**100.1**

Table 11
Statistics for Quantities Used in Calculation of Probability

Quantity	Relative standard deviation ($\tilde{\sigma}_M$)	Bias factor (δ)
Target heat flux	0.26	0.91

is reached. Using this time duration, an averaged critical heat flux is calculated from Eq. 1 which would result in a 17.5 TPP value in the same time period.

The calculated heat flux, which is used to determine the available occupying time displayed in Table 10, is assessed to determine the probability of being able to exceed the critical heat flux. This is done because FDS predicts the quantity of interest [55]. This probability is presented in column F. The probability calculated in column F is averaged and is recorded in Table 12. Column E and F are then repeated for every 100 s further into the simulation.

In Table 10, the available occupying times are presented for the different locations specified in Fig. 9. For each location, the available occupying time is calculated according to the time the location is occupied for after the fire's ignition. The cells not highlighted in bold display the time required for the location to reach a 17.5 TPP value. The cells highlighted in bold display a safe occupying time where the 17.5 TPP value is not reached before the simulation ends.

Because the simulations are within the validation range provided by McGrattan et al. [55], FDS model uncertainty statistics can be used to determine the probability (P) with Eq. 3.

$$P(x > x_c) = \frac{1}{2} erfc\left(\frac{x_c - \mu}{\sigma\sqrt{2}}\right) \tag{3}$$

The mean (μ) and standard deviation (σ) are calculated with Eq. 4 and Eq. 5, where (M) is the FDS predicted quantity of interest. The quantity of interest (x) is the heat flux and (x_c) is the critical heat flux.

$$\mu = \frac{M}{\delta} \tag{4}$$

$$\sigma = \tilde{\sigma}_M \frac{M}{\delta} \tag{5}$$

The bias factor (δ) and the relative standard deviation ($\tilde{\sigma}_M$) as presented by McGrattan et al. [55], are shown in Table 11.

Although Table 10 shows that the minimum TPP rating is not reached in specific locations, Table 12 shows that there is still a possibility of the critical heat flux being reached and therefore makes the minimum TPP rating achievable. In order to determine an acceptable probability, the probability of firefighters being injured

Table 12
Location of Critical Heat Flux Probability After Ignition of the Fire

Location entry time after ignition (s)	Probability of critical heat flux being reached in the occupying time at location					
	A1	A2	A3	A4	B1	B2
0	59.84%	60.03%	57.30%	60.30%	59.63%	61.89%
100	62.44%	62.32%	57.51%	59.38%	63.14%	60.72%
200	61.52%	61.03%	61.87%	60.05%	61.47%	61.97%
300	63.16%	62.51%	61.96%	52.03%	63.98%	63.15%
400	63.56%	63.51%	55.11%	38.04%	61.69%	62.56%
500	62.07%	59.39%	41.73%	25.08%	63.16%	58.95%
600	60.81%	56.59%	32.83%	9.83%	62.86%	56.54%
700	62.03%	58.52%	12.69%	0.34%	62.12%	56.39%
800	59.70%	55.66%	1.03%	0.00%	62.79%	52.05%
900	63.13%	30.32%	0.00%	0.00%	62.86%	20.22%
1000	62.53%	2.22%	0.00%	0.00%	62.04%	0.59%
1100	62.23%	0.00%	0.00%	0.00%	62.09%	0.00%
1200	2.56%	0.00%	0.00%	0.00%	2.49%	0.00%

Location entry time after ignition (s)	Probability of critical heat flux being reached in the occupying time at location					
	B3	C1	C2	C3	C4	D1
0	60.55%	58.09%	62.01%	64.81%	64.46%	59.40%
100	59.63%	61.26%	62.19%	62.53%	61.58%	61.17%
200	59.08%	61.92%	62.44%	60.65%	57.62%	62.77%
300	52.00%	63.37%	62.82%	53.13%	48.30%	63.43%
400	42.47%	63.33%	60.94%	44.25%	39.38%	63.90%
500	29.25%	62.51%	58.19%	32.73%	25.29%	62.48%
600	13.57%	61.54%	59.31%	15.42%	9.60%	62.06%
700	1.76%	63.37%	58.82%	1.83%	0.43%	63.46%
800	0.01%	62.93%	46.55%	0.01%	0.00%	62.50%
900	0.00%	62.52%	14.79%	0.00%	0.00%	63.34%
1000	0.00%	61.43%	0.38%	0.00%	0.00%	62.15%
1100	0.00%	62.06%	0.00%	0.00%	0.00%	61.82%
1200	0.00%	0.82%	0.00%	0.00%	0.00%	2.31%

when attending to a fire scene is investigated. For the live fire training scenario, it would be ideal to have the statistics of the number of training firefighters injured and the number of live fire training events. This was not available at the time of the study. In the controlled environment created in the live fire training structure, a firefighter should be less likely to sustain an injury than when attending an actual fire. Therefore, an acceptable probability will be provided when it is less than the probability of a firefighter being injured at an actual fire.

Unfortunately, a statistic for firefighters being injured at a fire scene in South Africa is not known. In order to compensate for this, international statistics have been investigated. The statistics must be specifically for the number of firefighters

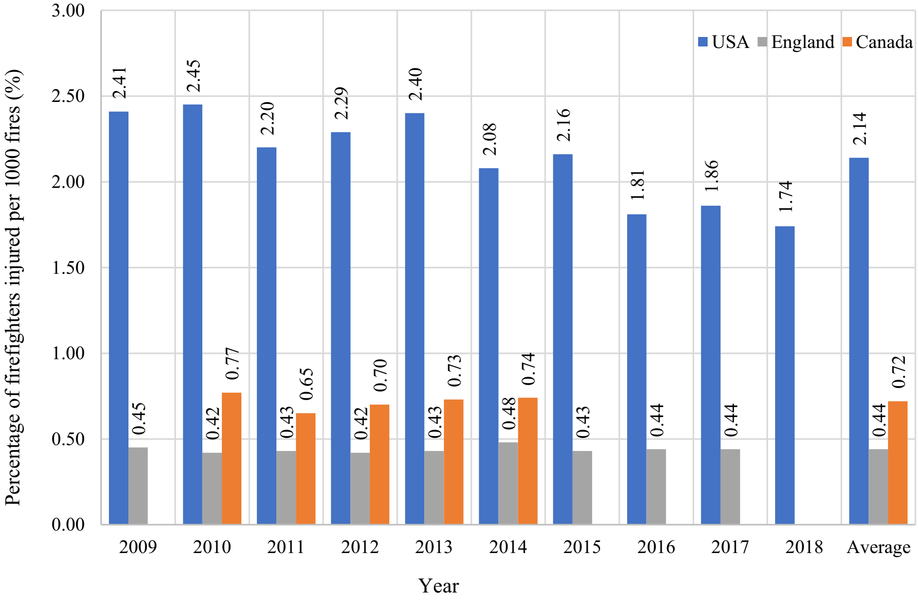

Figure 11. Annual percentage of firefighters injured per 1000 fires.

injured at a fire scene and the number of fires that occurred. Live fire training is for a fire incident. Therefore, using general-firefighter injury statistics will not be suitable as they contain injury statistics from non-fire incidents. The required information is available from the United States of America (USA), England and parts of Canada. In the USA, the statistics consist of the number of firefighter injuries. However, this was looked at more closely and it was found to be the number of firefighters injured [57].

In the USA, there is a 2.22% probability of a firefighter being injured at a fire scene. This is based on the most recent statistics that are available from Evarts, Molis [1]. In England, there is a 0.44% probability of a firefighter being injured at a fire scene [58, 59]. In Canada, using their available 4 out of 6 jurisdictions, there is a 0.72% probability of a firefighter being injured at a fire scene [60, 61]. These statistics are presented in Fig. 11.

When using these probabilities for injuries at actual fire scenes, the probability of a training firefighter being injured must be reduced to below 0.44% to be acceptable.

The available time specified in Table 10 has been recalculated for the time available before a 0.44% probability is achieved. This is done to ensure that there is insufficient probability in the estimated heat flux, as calculated by FDS, being capable of exceeding the critical heat flux. The results are displayed in Table 13. By finding the averaged highest probability that is below 0.44%, and locating the time it took to be achieved, the available time is identified.

Table 13
Available Time at Location Before a 0.44% Probability is Achieved

	Time available before a 0.44% probability at location (s)					
Location entry time after ignition (s)	A1	A2	A3	A4	B1	B2
0	41.6	107.9	182.0	247.0	41.6	122.2
100	29.9	88.4	149.5	202.8	32.5	110.5
200	27.3	75.4	119.6	187.2	31.2	92.3
300	26.0	66.3	117.0	189.8	27.3	85.8
400	27.3	75.4	135.2	224.9	29.9	88.4
500	28.6	81.9	152.1	258.7	31.2	96.2
600	28.6	107.9	232.7	386.1	32.5	119.6
700	35.1	153.4	374.4	599.3	42.9	161.2
800	42.9	179.4	462.8	499.2	45.5	192.4
900	49.4	210.6	399.1	399.1	52.0	228.8
1000	58.5	258.7	300.3	300.3	61.1	292.5
1100	72.8	200.2	200.2	200.2	75.4	200.2
1200	85.8	100.1	100.1	100.1	85.8	100.1

	Time available before a 0.44% probability at location (s)					
Location entry time after ignition (s)	B3	C1	C2	C3	C4	D1
0	286.0	41.6	114.4	258.7	292.5	37.7
100	248.3	36.4	132.6	231.4	260.0	32.5
200	237.9	39.0	132.6	222.3	254.8	33.8
300	237.9	36.4	132.6	222.3	256.1	31.2
400	253.5	39.0	139.1	244.4	283.4	33.8
500	282.1	41.6	150.8	270.4	317.2	37.7
600	361.4	41.6	175.5	365.3	422.5	37.7
700	508.3	53.3	217.1	523.9	599.3	46.8
800	499.2	58.5	236.6	499.2	499.2	52.0
900	399.1	63.7	265.2	399.1	399.1	57.2
1000	300.3	67.6	300.3	300.3	300.3	62.4
1100	200.2	81.9	200.2	200.2	200.2	74.1
1200	100.1	94.9	100.1	100.1	100.1	88.4

4. Discussion

The majority of heat flux intensity calculated in this study is similar to what has been recorded by others for live fire training (refer to Figs. 12, 13, 14 and 15) [62].

The scenario used in this study is of firefighters in the fire's room of origin. The results in Table 13 may change with various firefighting operations such as tactical ventilation or fire suppression and may be considered by changing the HRR or opening or closing of vents. The scenario selected is used to demonstrate a method for calculating the TPP value from the FDS results. The scenario may be

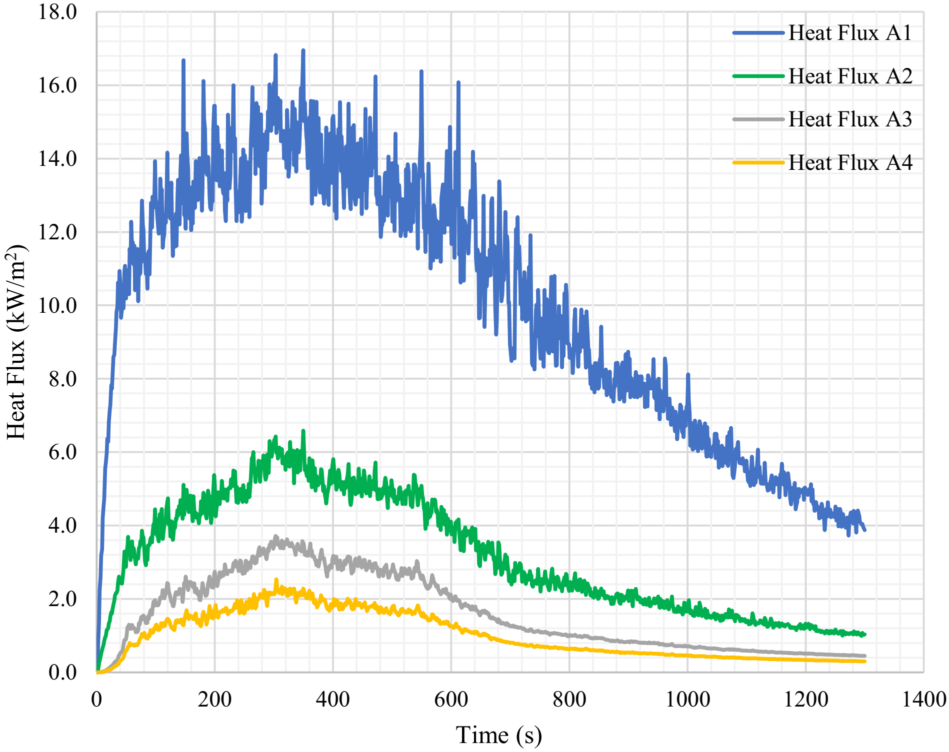

Figure 12. Ground floor—heat flux exposure in Location A.

extended past the fire's room of origin by following the same process in Fig. 10 and adding additional FDS heat flux devices in neighbouring compartments.

The results in Table 10 show how various locations around the fire require the time to be limited before a 17.5 TPP value is reached. This ensures that the available times specified in Table 10 are within the known tenable limits as explained in Table 4.

The location entry time after ignition is the time available to the firefighter once they have entered a specific location. The results represent a firefighter that moves into only one location. The results can be changed to allow for a firefighter to spend time in different locations. This may be done by using the TPP contributions from the occupied locations for the duration that the respective locations are occupied.

The probability of the calculated heat flux being able to exceed the critical heat flux was then calculated in Table 12. This result showed that there was significant probability in the FDS calculated heat flux being able to exceed the critical heat flux.

To determine what an acceptable probability is, firefighter injury statistics were assessed. At the time of this study, the probability for firefighter injury at actual fire scenes was found for multiple countries but was not found for firefighters dur-

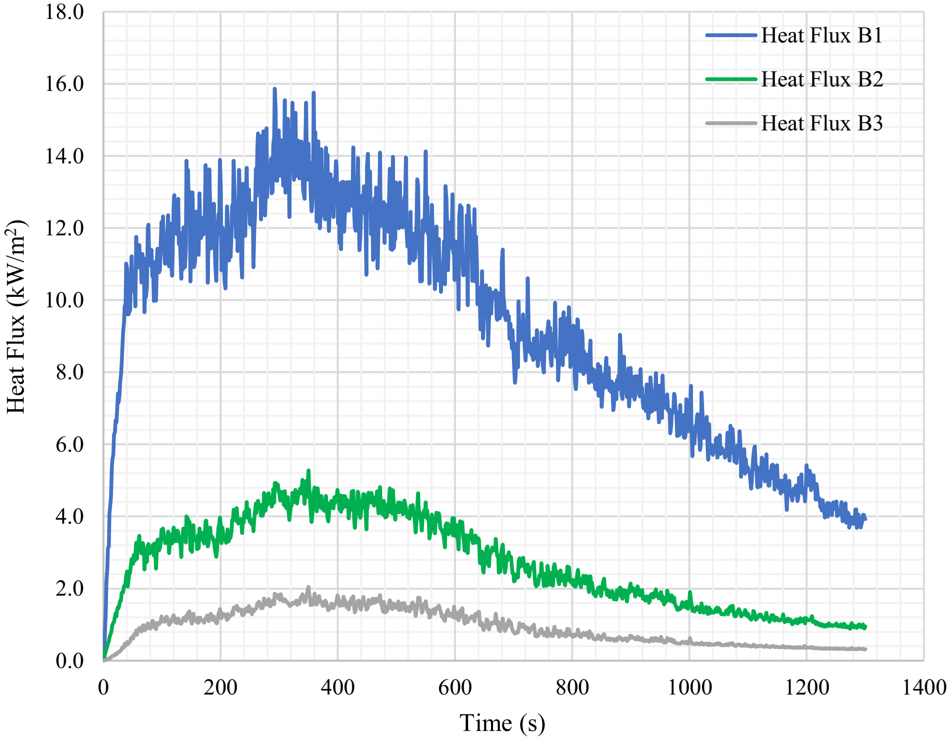

Figure 13. Ground floor—heat flux exposure in Location B.

ing live fire training. Although injury does occur during training, the probability is expected to be less than that of firefighters at a fire scene. Careful consideration of an acceptable probability will have to be considered by those wanting to perform this study.

When assessing the probability of values predicted by FDS, it is important that the user is careful of the input parameters used and the impact they have on results. Further guidance on input parameter uncertainty can be found in the FDS Validation Guide [55].

Table 13 shows the final result which has lower safe available times than that in Table 10. This is because the calculated average heat flux exposure must have a lower probability of exceeding the critical heat flux than the acceptable probability limit.

Knowing how much time is available to firefighters and from when this time is available could be used to plan their various operations that they may perform. For example, firefighters would not be expected to perform search and rescue operations when the conditions are such that their time is limited to under 60 s [29]. Table 13 shows that locations close to the fire have available times that are less than 60 s. Search and rescue operations would have to be limited in these locations until later location entry times.

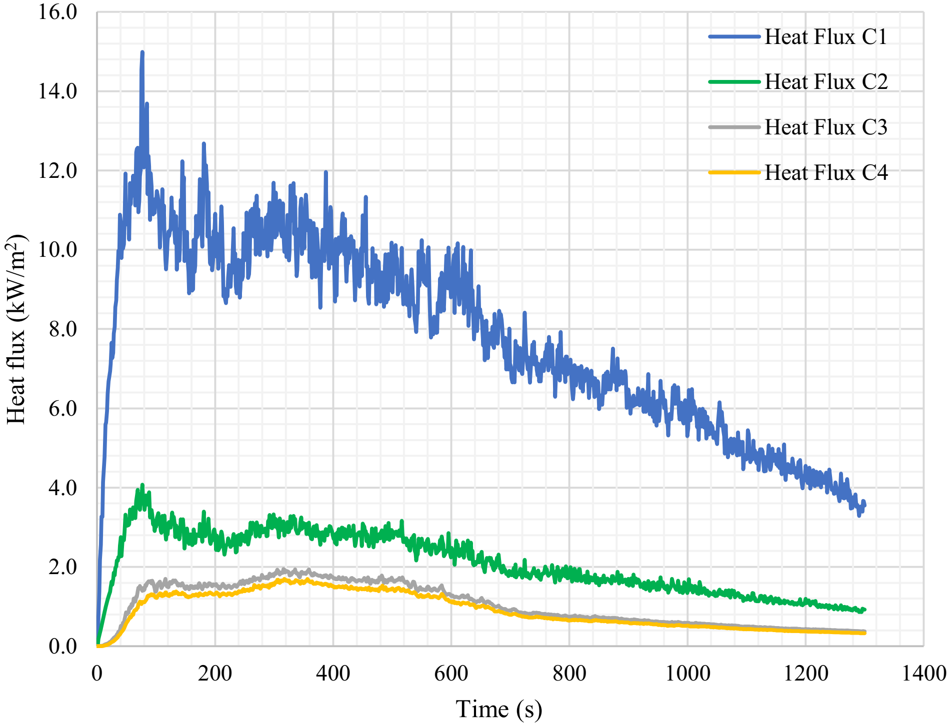

Figure 14. Ground floor—heat flux exposure in Location C.

The beam at ceiling level has not significantly affected the results (refer to Fig. 4). The results at B2 and C2 are from FDS devices that face horizontally toward the fire (refer to Table 8 and Fig. 9). This disregards any significant effect of the beam on the flow of hot gases under the ceiling. The results at B3 and C3 are from FDS devices with different orientations but have similar results in Table 13.

5. Conclusion

For assessing heat flux exposure, firefighter garments were investigated. It was found that the TPP test used to rate firefighter garments, could be used to assess a firefighter's critical heat flux exposure. Unlike other options for assessing a firefighter's critical heat flux exposure, the use of the TPP value had the benefits of being both readily available to be used and was consistent across a wide range of heat fluxes. It was also identified that the use of the 17.5 TPP value would sufficiently limit the heat flux exposure before causing bubbling and damage to the SCBA facepiece.

The use of the 17.5 TPP value can be used with available technology to assist with increasing the level of firefighter safety. By using FDS to estimate heat flux

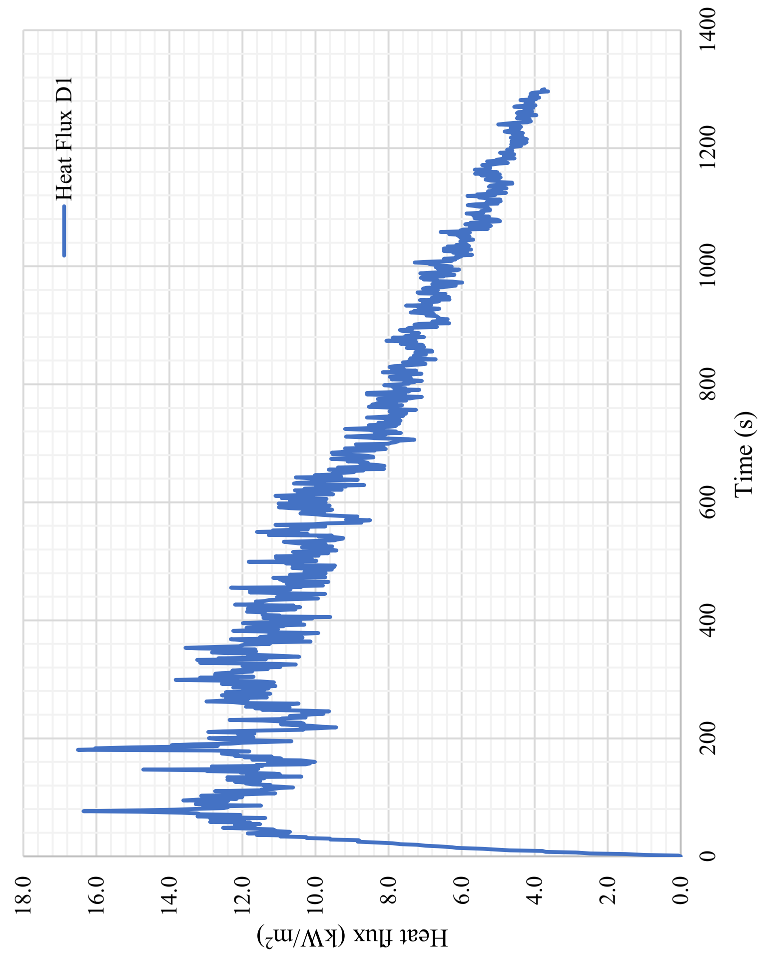

Figure 15. Ground floor—heat flux exposure in Location D.

exposure, the 17.5 TPP value was capable of determining the time and location that firefighters would be safe from critical heat flux exposures. The benefit for knowing this in live fire training is that it allows for the instructor in charge to determine whether the training objectives can be safely achieved with their training firefighters. It can also be used on the fireground to reduce the severity of burn injuries. This could be done by using it to assist with specifying safe working distances or for identifying the need of additional fire protection measures required to assist firefighters.

The key findings below have enabled the ASET at various locations around the fire source to be calculated in Durban's existing live fire training structure.

1. The minimum required TPP rating for firefighter garments produced a suitable range of heat flux exposure. This compared well to known firefighter limits for heat flux exposure. This has allowed for increased confidence with using the 17.5 TPP value.
2. A method is prepared for using the FDS heat flux output to determine when the 17.5 TPP value is reached and the time available for the corresponding heat flux to be within an acceptable probability. The ease and availability of accessing FDS allows this method to be readily available to help reduce firefighter exposure to excessive heat flux levels.

Acknowledgements

The authors thank Alex Gloster (Training Manager at eThekwini Metro Council Fire & Emergency Services) for providing information on Durban's existing live fire training structure.

Code Availability

CFD software used is FDS, which is freely available from the internet.

Data Availability

The FDS output files are available.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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