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Fire resistance requirements in single-storey industrial and warehouse buildings

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Preface

This report has been prepared as part of a research project on limiting fire spread by design where this part of the project investigated the fire resistance requirements for external walls near a boundary in single-storey industrial and warehouse buildings.

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Abstract

An investigation into fire resistance requirements applied to external walls located near a property boundary in single-storey industrial and warehouse buildings in New Zealand has been carried out. Currently specified fire resistance ratings in prescriptive compliance documents are much higher than similar requirements in many overseas jurisdictions. The aim of this study was to understand why this is the case and to propose a risk-based methodology for setting appropriate levels of fire resistance in regulation.

A probabilistic analysis using Latin hypercube sampling methods in conjunction with a fire severity model known as the graphical time-equivalence method has been used to construct probability distributions for the required fire resistance ratings. Cumulative frequency distribution curves showing the fire resistance percentiles are presented. It was found that the methodology can be applied to buildings within the scope of C/AS5 but may not be strictly applicable to very high load densities such as warehouses in C/AS6 due to the underlying limitations of the parametric time-temperature equations. It is concluded that current fire resistance levels in C/AS5 and C/AS6 for external boundary walls could be reduced, depending on the level of acceptable risk and the design percentile values set by the regulator.

Keywords

Fire resistance, external walls, risk assessment, probabilistic analysis, industrial buildings, Monte Carlo, time-equivalence, FRR.

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1. Introduction

This report describes an investigation into fire resistance requirements in single-storey industrial and storage buildings in New Zealand. It is particularly relevant for external walls located near a property boundary, as often these are the only walls required to be fire rated in these types of building (for example, see Figure 1). It is also common for lightweight roof structures in these buildings to be non-fire rated, and when exposed to fire, they can be susceptible to earlier collapse. This also can lead to flames and energy venting through the roof accompanied by a corresponding reduction in the thermal exposure experienced by the boundary walls. Based on current Fire and Emergency New Zealand (FENZ) operating practices, given the high risk of collapsing roofs and the low risk to escaping occupants, it is unlikely firefighters would commit to enter these buildings unless their visibility within the building was relatively good.

It has been noted that currently specified fire resistance ratings in the New Zealand prescriptive compliance documents C/AS5 (MBIE, 2017a) and C/AS6 (MBIE, 2017b) are much higher than similar requirements in many overseas jurisdictions. This study sought to understand why this is the case and to propose a risk-based methodology for setting appropriate levels of fire resistance in regulation.

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Figure 1. Boundary wall (left) in an industrial building typically requires fire rated construction with no unprotected openings.

Building codes typically require certain structural and separating elements such as walls and floors to withstand a fully developed fire to provide a particular function. This might be to ensure occupants have sufficient time to escape a fire, to prevent fire spreading between different areas in a building or to prevent collapse of a building. Fire resistance ratings are usually specified depending on the particular objective and other factors concerning the type and use of the building. Elements of construction are assigned fire resistance ratings based on the duration that they successfully satisfy specific criteria in a standard fire resistance test such as AS 1530.4:2014 (Standards Australia, 2014). .

The New Zealand Building Code (NZBC) includes objectives to safeguard people from an unacceptable risk of injury or illness caused by fire, protect other property from damage caused by fire and facilitate firefighting and rescue operations (DBH, 2012). External walls close to property boundaries are commonly fire rated to help prevent fire spread to neighbouring property.

The philosophy of the current NZBC protection from fire Acceptable Solutions was introduced in 2012. The current approach is to provide a means of demonstrating compliance that is “deemed to satisfy” the NZBC protection from fire clauses in a simple manner that does not require any engineering analysis. Design settings (such as fire resistance requirements) were chosen so that they would apply regardless of detailed building characteristics. The intention was for the Acceptable Solutions to be conservative for all buildings that could be designed to them. Because they did not capture detailed characteristics that may ultimately affect the fire risk, the level of conservatism varies for specific building designs. Seven Acceptable Solutions are targeted at major occupancy classifications (MBIE, 2014a).

Prescriptive requirements for fire resistance ratings in industrial and storage buildings are given in NZBC C/AS5 Acceptable Solution for buildings used for business, commercial and low-level storage (MBIE, 2017a) and C/AS6 Acceptable Solution for buildings used with high level storage and other high-risk purposes (MBIE, 2017b). The property ratings in the Acceptable Solutions C/AS5 and C/AS6 are in the range 120–180 minutes for unsprinklered buildings and 60–180 minutes for sprinklered buildings. The buildings mainly covered by this research (although not all buildings covered by C/AS5 and C/AS6) commonly have an exposed and unrated roof structure. This means that burn-through or venting of heat and smoke is more likely compared to buildings where internal ceilings provide a barrier reducing the ease with which roof venting may occur, thus containing more of the heat within the building. Figure 2 shows an aerial view of the outcome from a fire in a New Zealand building with an unrated roof structure. The light steel roof has partially collapsed allowing venting, and minimal damage is visible on the adjacent building.

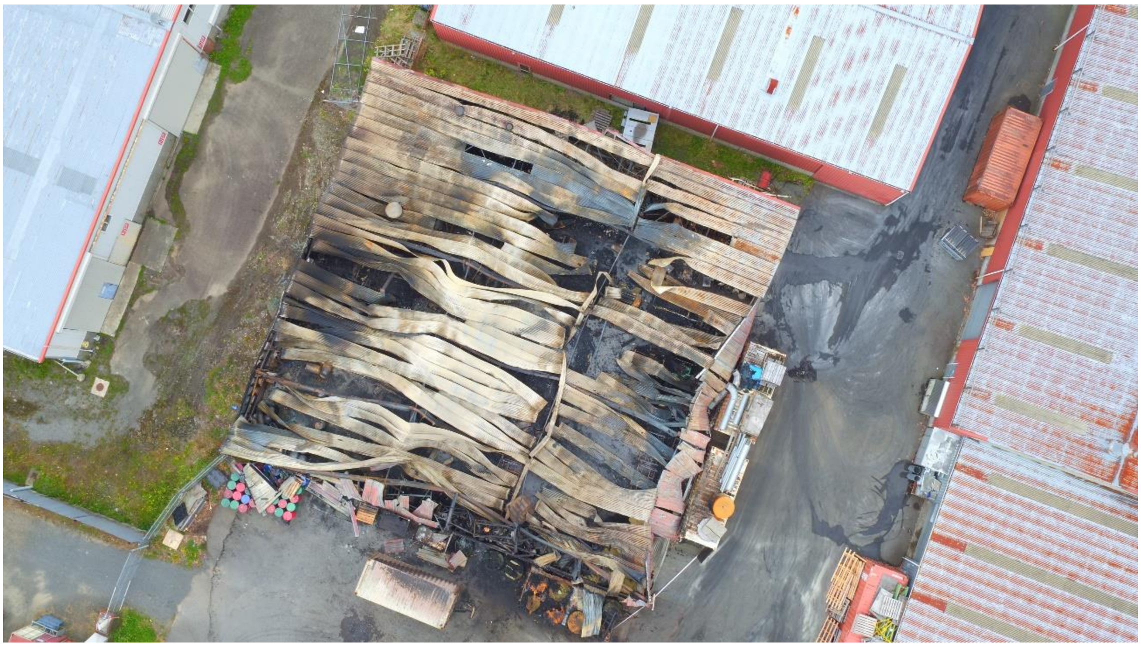

Figure 2. Aerial photo of the outcome of a fire in this type of building in New Zealand (Fire and Emergency New Zealand).

A related trend especially in Auckland is to build warehouses on the boundary on at least one if not more boundaries. Typically, these are tilt slab and thus have very few openings.

The research includes a risk-based analysis of fire resistance requirements for these types of building to provide the regulators with new information to allow them to review the existing requirements and, if appropriate, make changes.

In this report, the term ‘boundary fire wall’ will be used to refer to parts of an external wall where, due to proximity to a relevant boundary, a fire resistance rating is required.

2. Comparison of code requirements

This section presents an overview of fire resistance ratings required for industrial and storage buildings in various international jurisdictions including New Zealand. While most of these countries permit performance-based design, the material presented here is based on prescriptive requirements as specified in Acceptable Solutions, deemed-to-satisfy requirements, codes of practice or similar documents.

2.1 New Zealand

2.1.1 Acceptable Solutions

The Acceptable Solutions as published in 2017 provide for two categories of fire resistance rating: life ratings and property ratings. The former is specified where the requirement is to ensure occupants have adequate time to safely escape from the building. The latter is specified where there is a requirement to ensure parts of the building can withstand a full burnout of the fire so that the risk of fire spread to other property or the threat to firefighters is acceptably low. The relevant Acceptable Solutions for this study are C/AS5 (MBIE, 2017a) and C/AS6 (MBIE, 2017b). These Acceptable Solutions only apply to buildings that are no more than 20 storeys high (from ground level).

The scope of C/AS5 applies to risk group WB. This covers buildings or parts of buildings where people work and specifically includes:

- offices (including professional services such as law and accountancy practices)
- industrial buildings such as factories, processing and manufacturing plants (excluding foamed plastics) and may include temperature-controlled storage up to a maximum area of 500 m^2 with a maximum capable of storage height of 5.0 m
- buildings or parts of buildings capable of less than 5.0 m storage height
- warehouses and storage buildings capable of storage of 5.0 m or greater but with a height to apex of less than 8.0 m and building floor area of less than 4200 m^2
- temperature-controlled storage capable of less than 3.0 m high storage height
- laboratories and light aircraft hangars
- normally unoccupied buildings such as buildings containing plant or fixed machinery only and spray painting operations whether or not within a spray booth.

Fire ratings given in C/AS5 paragraphs 2.3.1 and 2.3.2 are summarised in Table 1. Property ratings range from 60 to 180 minutes depending on storage height, distance to a relevant boundary and whether fire sprinklers are installed.

Table 1. C/AS5 fire resistance ratings.

C/AS5	Life rating	Property rating
>3.0 m storage height and < 15 m to relevant boundary	60 min without sprinklers 30 min with sprinklers	180 min without sprinklers 90 min with sprinklers
Otherwise		120 min without sprinklers 60 min with sprinklers

The scope of C/AS6 applies to risk group WS. This covers buildings or parts of buildings capable of storage of goods and other materials at a height of 3.0 m or more (warehouses with storage 5.0 m or more) and other spaces where there is a high fire load or the potential for fast fire growth. It specifically includes:

- warehouses capable of storage over 5.0 m in height except storage buildings capable of storage of 5.0 m or greater but with a height to apex of less than 8.0 m and floor area of less than 4200 m^2 (see C/AS5)
- supermarkets with shelving over 3.0 m
- bulk retail and wholesalers with greater than 3.0 m storage height
- temperature-controlled storage with a stack height of more than 3.0 m except limited areas in processing buildings (see C/AS5).

C/AS6 specifies a life rating of 60 minutes and a property rating of 180 minutes. C/AS6 also requires automatic fire sprinklers to be installed.

Exterior walls require a fire resistance rating if parts of the wall are not permitted to be unprotected. This depends on the distance the wall is from a relevant boundary and the length and height of the wall. The proportion of the wall required to be fire rated decreases as the distance from the relevant boundary increases. The dominant mechanism for fire spread across a boundary is assumed to be due to radiation heat transfer. The area of the external wall permitted to be unprotected is determined such that the received radiation at the boundary is limited to 30 kW/m^2 and at a distance 1 m beyond the boundary limited to 16 kW/m^2 (MBIE, 2014b). Unprotected areas are only permitted in external walls more than 1 m from the boundary with the permitted area increasing with distance until eventually 100% of the area may be unprotected meaning there is no fire resistance requirement.

For a wall located within 1 m of a relevant boundary or if the building is higher than 10 m, the specified fire resistance rating must be achieved considering fire exposure separately to each side of the wall (i.e. two-way fire resistance rating). For other cases, the specified fire resistance rating must be achieved considering fire exposure to only the interior side of the wall (i.e. one-way fire resistance rating).

2.1.2 Pre-2012 C/AS1 requirements

The NZBC Acceptable Solution approach prior to 2012 was more detailed. Fire resistance ratings were specified as either F-ratings (to protect occupants, adjacent household units and sleeping areas in the same building and firefighters – equivalent to the life requirement in the current Acceptable Solutions) or S-ratings (intended to prevent fire spread for the complete burnout of the firecell). All single-floor industrial or commercial buildings at all occupant loads had an F-rating of 0. The S-ratings given in C/AS1 Table 5.1 and reproduced as Table 2 were derived from the Eurocode time-equivalent formula. C/AS5 buildings with a storage height less than 3 m would fit within Fire Hazard Category 3 or less. As indicated in the notes to the table, Fire Hazard Category 4 (which would be equivalent to many C/AS5 and C/AS6 buildings) required specific fire engineering design. Notes 4 and 5 are also particularly relevant for buildings in this study. Given this table, the equivalent simplified, conservative FRR requirement that would cover all single-storey industrial/warehouse buildings with an unrated roof would be 120 minutes unsprinklered, 60 minutes sprinklered, which matches the current C/AS5 requirement. An additional comment regarding Fire Hazard Category 4 firecells noted that specific fire engineering design for fire hazard category 4 will typically commence with the design of an active protection system. It also said this system must be purpose designed to meet the design fire hazard for the particular application and to control a developing fire.

Table 2. Pre-2012 C/AS1 Table 5.1 (DBH, 2005).

Table 5.1: **Values of t_e for Calculating the S Ratings for Fire Hazard Categories 1, 2 and 3**
Paragraphs 2.2.1, 5.5.2, 5.5.3, 6.10.5, 6.20.15

	Fire Hazard Category 1 (FLED = 400 MJ/m²)					Fire Hazard Category 2 (FLED = 800 MJ/m²)					Fire Hazard Category 3 (FLED = 1200 MJ/m²)				
	A_h/A_f					A_h/A_f					A_h/A_f				
A_v/A_f	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20
0.05 or less	90	60	50	40	40	180	120	100	80	80	240	180	140	140	120
0.06	80	50	50	40	40	160	110	90	80	80	240	160	140	120	110
0.07	70	50	40	40	40	150	100	80	80	70	220	160	140	120	110
0.08	70	50	40	40	30	140	90	80	70	70	220	140	120	110	100
0.09	60	40	40	30	30	140	90	80	70	70	200	140	110	110	100
0.10	60	40	40	30	30	120	80	70	70	70	180	140	110	100	100
0.11	50	40	30	30	30	110	80	70	70	60	160	120	110	100	100
0.12	50	40	30	30	30	100	70	70	60	60	160	110	100	100	90
0.13	50	40	30	30	30	100	70	70	60	60	160	110	100	90	90
0.14	50	30	30	30	30	90	70	60	60	60	140	100	100	90	90
0.15	40	30	30	30	30	80	70	60	60	60	120	100	90	90	90
0.16	40	30	30	30	30	80	60	60	60	60	110	100	90	90	90
0.17	40	30	30	30	30	80	60	60	60	60	110	90	90	90	90
0.18	40	30	30	30	30	70	60	60	60	60	110	90	90	90	80
0.19	30	30	30	30	30	70	60	60	60	60	110	90	90	80	80
0.20	30	30	30	30	30	70	60	60	60	60	100	90	80	80	80
0.25 or greater	30	30	30	30	30	60	60	50	50	50	90	80	80	80	80

Notes:

1. **Determining S rating**
   $S = kt_e$ where k = 1.0 for unsprinklered *firecells* and 0.5 for sprinklered *firecells*. Therefore in this table the t_e values are the same as the *S ratings* for unsprinklered *firecells*.
2. **Interpretation**
   A_f = floor area of *firecell* (m²)
   A_v = area of vertical openings in *external walls* of the *firecell* (m²)
   A_h = area of horizontal openings in roof of *firecell* (m²)
   Linear interpolation is permitted where values of A_v/A_f or A_h/A_f lie between those given in the table.
3. **Location of openings**
   Openings to allow *fire* venting should be located in the most practicable manner to provide effective cross-ventilation. This reduces structural *fire* severity and facilitates *fire* fighting operations.
4. **Effective openings**
   a) Only those areas of *external walls* and roofs which can dependably provide airflow to and from the *fire* shall be used in calculating A_v and A_h. Such areas include windows containing non-*fire* resistant glass and likely to break shortly after exposure to significant heat.
   b) An allowance can be made for air leakage through the *external wall* of the *building* envelope. The allowance for inclusion in A_v shall be no greater than 0.1% of the *external wall* area where the wall is lined internally, and 0.5% if unlined.
   c) Only roof venting which is specifically designed to open or melt rapidly in the event of *fire* shall be included in the area A_h.
   d) For single floor *buildings* or the top floor of multi-floor *buildings*, where the structural system supporting the roof is non-rated and directly exposed to the *fire* (i.e. no ceiling installed), A_h/A_f may be taken as 0.2.
5. **Areas not regarded as openings**
   For the purpose of calculating A_v it shall be assumed that doors in *external walls* are closed. Wall areas clad in sheet metal shall not be included in the area A_v.
6. **Intermediate floors**
   Where a *firecell* contains *intermediate floors*, separate calculations shall be made to determine t_e, first by taking A_f as the total floor area in the *firecell* (as defined in Paragraph 2.3.3), then by taking A_f separately as the floor area of each level. The highest value of t_e shall be used to determine the *S rating*.
7. **Background to table**
   Table 5.1 is derived using Equation E3 from Annex E, Eurocode DD ENV 1991-2-2: 1996, Eurocode 1: Basis of Design and Actions on Structures, Part 2.2 Actions on Structures Exposed to Fire (together with United Kingdom National Application Document); British Standards Institution, London, England. A *firecell* height of 3.0 m has been assumed and a thermal inertia factor corresponding to the most severe conditions (i.e. those which generate the highest t_e values and which correspond to use of k_b = 0.09 in Equation E3) for typical materials of *firecell construction*. For *firecells* which differ from these assumptions, especially with regard to the materials of *construction*, more accurate answers may be obtained with specific *fire* engineering design, which is mandatory for *fire hazard category* 4.

2.1.3 Verification Method C/VM2

The Verification Method C/VM2 for NZBC clauses C1–C6 *Protection from fire* provides for scenarios where the external wall is required to have a fire resistance rating to resist the full burnout design fire described in C/VM2 paragraph 2.4. The full burnout design fire does not include the effect of fire sprinklers (if present) or firefighting intervention. However, a reduction in the design fire load energy density is permitted where sprinklers are installed.

C/VM2 describes three choices for calculating the full burnout design fire:

- Use a time-equivalent formula to calculate the equivalent fire severity and specify building elements with a fire resistance rating not less than the calculated fire severity. In this case, an equivalent fire severity of 20 minutes shall be used if the calculated value is less.
- Use a parametric time versus gas temperature formula to calculate the thermal boundary conditions (time/temperature) for input to a structural response model.
- Construct an HRR versus time structural design fire. Then, taking into account the ventilation conditions, use a fire model or energy conservation equations to determine suitable thermal boundary conditions (time/temperature/flux) for input to a structural response model.

The first approach using a time-equivalence formula is described in detail in C/VM2 with equations given from Annex E of Eurocode DD ENV 1991-2-2. The second and third approaches are not described in any further detail.

The time-equivalence formula was used as the basis for the calculated S-ratings presented in Table 2 of pre-2012 C/AS1. It takes into account the thermal characteristics of the enclosure construction, the area of openings in wall and/or roof and the amount of fire load present.

C/VM2 allows a ratio of 0.20 to be used for the roof ventilation area to floor area for single-storey buildings (or the top floor of multi-storey buildings) where the structural system supporting the roof is exposed to view and has no dependable fire resistance. This would generally be applicable to the buildings considered in this research.

The design fire load energy density (FLED) values given in C/VM2 are shown in Table 3. Industrial buildings with storage up to 3 m high would generally require a design FLED of 1200 MJ/m^2, and those with storage above 3 m require a design FLED of 800 MJ/m^2 per m of storage height.

Table 3. C/VM2 Table 2.2 Design FLEDs (MBIE, 2014b).

Table 2.2	**Design FLEDs for use in modelling fires in C/VM2**		
Design *FLED* (MJ/m²)	Activities in the space or room	Examples	
400	1. Display or other large open spaces; or other spaces of low *fire hazard* where the occupants are awake but may be unfamiliar with the *building*.	1. Art galleries, auditoriums, bowling alleys, churches, clubs, community halls, court rooms, day care centres, gymnasiums, indoor swimming pools	
	2. Seating areas without upholstered furniture	2. School classrooms, lecture halls, museums, eating places without cooking facilities	
	3. All spaces where occupants sleep	3. *Household units*, motels, hotels, hospitals, residential care institutions	
	4. Working spaces and where low *fire hazard* materials are stored	4. Wineries, meat processing plants, manufacturing plants	
	5. Support activities of low *fire hazard*	5. Car parks, locker rooms, toilets and amenities, service rooms, plant rooms with no plant using flammable or *combustible* fuels	Amend 3 Dec 2013
800	1. Spaces for business	1. Banks, personal or professional services, police stations (without detention), offices	Amend 3 Dec 2013
	2. Seating areas with upholstered furniture, or spaces of moderate *fire hazard* where the occupants are awake but may be unfamiliar with the *building*	2. Nightclubs, restaurants and eating places, *early childhood centres*, cinemas, *theatres*, libraries	
	3. Spaces for display of goods for sale (retail, non-bulk)	3. Exhibition halls, shops and other retail (non bulk)	
1200	1. Spaces for working or storage with moderate *fire hazard*	1. Manufacturing and processing moderate *fire load* 2. Storage up to 3.0 m high other than *foamed plastics*	
	2. Workshops and support activities of moderate *fire hazard*	3. Maintenance workshops, plant and boiler rooms other than those described elsewhere	Amend 3 Dec 2013
400/tier of car storage	Spaces for multi-level car storage	Car stacking systems. The design floor area over which the design *FLED* applies is the total actual car parking area	
800/m height, with a minimum of 2400	1. Spaces for working or storage with high *fire hazard*	1. Chemical manufacturing and processing, feed mills, flour mills 2. Storage over 3.0 m high of *combustible* materials, including climate controlled storage	
	2. Spaces for display and sale of goods (bulk retail)	3. Bulk retail (over 3.0 m high)	

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2.2 Australia

The National Construction Code (ABCB, 2015) contains requirements for the fire resistance of construction. Warehouses are considered to be Class 7b buildings, whereas industrial buildings would typically be considered to be Class 8.

Single-storey Class 7b and 8 buildings require Type C construction (i.e. can be combustible), and boundary fire walls require fire resistance levels of 90 minutes if within 1.5 m of the boundary, 60 minutes if within 1.5–3.0 m of the boundary and no fire resistance if more than 3.0 m from the boundary. The maximum compartment area for Type C construction in these buildings is 2000 m^2 increasing to 5000 m^2 for Type A construction (non-combustible).

In the case of external walls, these fire resistance ratings only apply for fire exposure from the exterior side, and there is no sprinkler benefit provided.

2.3 Scotland

The fire section of the Technical Handbook – Non-domestic (Scottish Government, 2017) gives the following fire resistance requirements for boundary fire walls in single-storey factory and storage buildings.

- Storage buildings without sprinklers fitted – at least 60 minutes fire resistance rating for the boundary wall when located more than 1 m from the boundary.
- Storage buildings with sprinklers fitted –at least 30 minutes fire resistance rating for the boundary wall when located more than 1 m from the boundary.
- Factory (class 2) buildings without sprinklers fitted –30 minutes fire resistance rating for the boundary wall when located more than 1 m from the boundary.
- Factory (class 2) buildings with sprinklers fitted –no fire resistance rating for the boundary wall when located more than 1 m from the boundary.
- Factory and storage buildings with or without sprinklers – 60 minutes fire resistance rating for the boundary wall when located not more than 1 m from the boundary.

In all cases, the direction of fire exposure need only be from the interior side.

2.4 England and Wales

Approved Document B (MHCLG, 2006) typically requires fire resistance ratings of 30 minutes with sprinklers or 60 minutes without sprinklers for external walls in single-storey industrial and storage occupancies.

BS 9999:2008 *Fire safety in the design, management and use of buildings. Code of practice* typically requires fire resistance ratings of 30 minutes sprinklered or 60 minutes unsprinklered for external walls in single-storey industrial and storage occupancies (BSI, 2008). The standard categorises industrial buildings as low, ordinary and high hazard.

2.5 United States of America

The International Building Code (International Code Council, 2015) categorises buildings by occupancy use. The main categories of interest in this study are F, S and H.

Factory industrial Group F occupancy includes uses such as assembling, disassembling, fabricating, finishing, manufacturing, packaging, repair or processing operations that are not classified as hazardous (Group H) or storage (Group S). There are two subcategories – F-1 moderate hazard and F-2 low hazard.

High hazard Group H includes the manufacturing, processing, generation or storage of materials that constitute a physical or health hazard in quantities in excess of the maximum allowable quantity limits for control areas specified elsewhere in the IBC. Hazardous occupancies have subcategories Groups H-1, H-2, H-3, H-4 and H-5.

Storage Group S occupancy includes storage uses that are not otherwise in Group H. It excludes spaces with floor area up to 9.3 m^2 that are an accessory to another occupancy. Storage occupancies have two subcategories – S-1 and S-2.

Storage Group S-2 occupancies include those used for the storage of non-combustible materials. This also allows non-combustible products on wood pallets or in paper cartons with or without single-thickness divisions or in paper wrappings. A negligible amount of plastic trim such as knobs, handles or film wrapping is permitted.

Storage Group S-1 generally cover those uses that are not S-2. Fire resistance ratings required for boundary walls are generally as follows:

- High hazard occupancy Group H – 180 minutes with no sprinkler benefit.
- Factory and industrial F1 and storage S1 – 120 minutes with no sprinkler benefit.
- Factory and industrial F2 and storage S2 – 60 minutes with no sprinkler benefit.

For non-loadbearing parts of these boundary walls, a lesser rating for the insulation and integrity criteria of the fire resistance test may be permitted depending on type of construction and distance to the boundary where more than 5 ft (1.52 m) as given in Table 602 of the IBC. The above fire resistance ratings also reduce as the distance from the boundary increases.

2.6 Canada

The National Building Code of Canada (NRC, 2015) Table 3.1.2.1 categorises buildings by occupancy use, with Group F applying to industrial buildings. The main categories of interest in this study are Group F, Division 1 (high-hazard industrial occupancies), Division 2 (medium-hazard industrial occupancies) and Division 3 (low-hazard industrial occupancies).

Paragraph 3.1.7.2 allows the insulation performance criterion for external walls to be waived where the limiting distance is 1.2 m or more provided correction is made for radiation from the unexposed face.

For a Group F Division 3 occupancy, the minimum required fire resistance rating for the external wall is in the range 45–60 minutes depending on the maximum permitted area of unprotected openings as a percentage of the exposing building face, the type of construction and the type of cladding. For a Group F Division 1 and 2 occupancy, the minimum required fire resistance rating for the external wall is in the range 1–2 hours (NBCC Table 3.2.3.7).

An exposed building face in a Group F Division 3 occupancy is permitted to be unrated provided it is of non-combustible construction and is a non-loadbearing wall with a limiting distance not less than 3 m (NBCC paragraph 3.2.3.11).

2.7 Summary

Table 4 summarises and compares fire resistance ratings for a number of codes and standards from the UK (England, Wales and Scotland), USA, Canada and Australia with the general requirements given in the NZBC Acceptable Solutions C/AS5 and C/AS6. Table 5 compares requirements for a set of specific example buildings. In most cases, the boundary wall fire ratings in C/AS5 and C/AS6 are significantly higher than would be the case for the equivalent situation in other comparable countries. It is also noted that there are differences in which direction external walls are required to be tested commonly with a requirement to test from both sides separately where the wall is within 1 m of the boundary. However, Australia only requires testing from the exterior side, while Scotland only requires testing from the interior side.

Table 4. Boundary wall fire ratings in single-storey industrial and storage buildings.

	NZ C/AS5 Property rating for external wall not permitted to be unprotected	NZ C/AS6 Property rating for external wall not permitted to be unprotected	England & Wales Approved Document B	UK BS9999	USA IBC	Scotland	NCC Australia	NBC Canada
Laboratories, workshops, manufacturing, factories, processing Temperature controlled storage (capable of <3.0 m storage height) Other storage buildings capable of <5.0 m storage height light aircraft hangars.	≥3.0 m storage height and < 15 m to relevant boundary 180 min without sprinklers 90 min with sprinklers < 3.0 m storage height or >= 15 m to RB 120 min without sprinklers 60 min with sprinklers	Out of scope	60 minutes without sprinklers 30 minutes with sprinklers	Low hazard 30 minutes, with or without sprinklers Ordinary hazard 60 minutes without sprinklers, 30 minutes with sprinklers	Low-hazard factory industrial, Group F-2 or Storage Group S-2 60 minutes with or without sprinklers Moderate-hazard factory industrial, Group F-1 or Storage Group S-1 120 minutes with or without sprinklers	Factory buildings with sprinklers require no fire resistance when located more than 1 m from the boundary. Factory and storage buildings require 60 min fire resistance rating with sprinklers when located not more than 1 m from the boundary. Factory buildings without sprinklers require 60 min when located not more than 1 m from the boundary; or 30 min if more than 1 m. See also below.	Class 7b and Class 8 buildings require 90 minutes if within 1.5 m of the boundary; 60 minutes if within 1.5 – 3.0 m of the boundary; and no fire resistance if more than 3.0 m from the boundary.	Group F Division 3 (low hazard industrial) 45 - 60 min No fire resistance required if wall is non-combustible, nonloadbearing and located more than 3 m from the boundary.

	NZ C/AS5 Property rating for external wall not permitted to be unprotected	NZ C/AS6 Property rating for external wall not permitted to be unprotected	England & Wales Approved Document B	UK BS9999	USA IBC	Scotland	NCC Australia	NBC Canada
Warehouses (capable of ≥5.0 m storage height) Temperature controlled storage (capable of ≥3.0 m storage height) Trading and bulk retail (≥3.0 m storage height)	Out of scope	Sprinklers required FRR 180 minutes	60 minutes without sprinklers 30 minutes with sprinklers	Ordinary hazard 60 minutes without sprinklers, 30 minutes with sprinklers High hazard 90 minutes without sprinklers, 60 minutes with sprinklers	Storage Group S-2 60 minutes with or without sprinklers Storage Group S-1 120 minutes with or without sprinklers High Hazard Group H 180 minutes with or without sprinklers	Storage buildings require 60 min fire resistance rating with sprinklers when located not more than 1 m from the boundary, or 30 min if more than 1 m. Storage buildings require 60 min fire resistance rating without sprinklers.	Class 8 buildings require 90 minutes if within 1.5 m of the boundary; 60 minutes if within 1.5 – 3.0 m of the boundary; and no fire resistance if more than 3.0 m from the boundary.	Group F Division 1 (high hazard industrial) Group F Division 2 (medium hazard industrial) 60 – 120 min

Table 5. Comparison of fire resistance rating of the external wall for a set of example buildings.

	NZ C/AS5 Property rating for external wall not permitted to be unprotected	NZ C/AS6 Property rating for external wall not permitted to be unprotected	England & Wales Approved Document B	UK BS9999	USA IBC	Scotland	Australia	Canada
EXAMPLE Storage building with wall on the boundary and 6 m storage height of low hazard product with sprinklers	Out of scope	180 min	30 min	30 min	60 min	60 min	90 min	45 - 60 min
EXAMPLE Storage building with wall 3 m from boundary and 4 m storage height of moderate hazard product without sprinklers	180 min	Out of scope	60 min	60 min	120 min	60 min	60 min	60 – 120 min
EXAMPLE Factory building 10 m from boundary including 2.5 m storage height without sprinklers.	120 min	Out of scope	60 min	60 min	120 min	30 min	0 min	0 - 60 min
EXAMPLE Factory building 10 m from boundary, moderate hazard, no storage, with sprinklers.	60 min	Out of scope	30 min	30 min	120 min	0 min	0 min	0 - 60 min

3. Determining fire resistance requirements

While the Acceptable Solutions prescribe what fire resistance rating is required for the various parts of a building, Verification Method C/VM2 or use of Alternative Solutions provide engineers with other options to determine what level of fire resistance is adequate to satisfy the functional requirements in the NZBC.

There are two main approaches used to determine what level of fire resistance is adequate such that functional requirements are met:

- Structural fire engineering design based on the expected fire dynamics and thermal and structural response of the building. This would treat the fire exposure as a design load to be resisted. This is rarely done as it can be complex and expensive, and given the state of the art, detailed design methods and factors of safety are generally not universally agreed. This type of analysis would usually be specifically directed at determining the structural adequacy of the building structure when exposed to fire.
- Application of time-equivalence methods where a calculation is made to determine the duration in a standard fire resistance test that would provide an equivalent thermal exposure due to a real fire (including the cool-down or decay period) given knowledge of the specific fire load, ventilation and thermal characteristics of the building. This is currently the general basis for the fire resistance ratings given in the Acceptable Solutions.

This research utilises the second approach where we apply the methodology to a population of buildings of a similar occupancy type to inform what levels of fire resistance might be acceptable for inclusion in prescriptive codes and standards.

The methods used here are generally not appropriate for the structural fire engineering design of a specific building, although they have sometimes been permitted for that purpose – for example, in C/VM2. There may be some justification for their use in relation to specific buildings where the effort and cost of a more detailed thermal and structural analysis is not warranted or not possible. However, it is more useful for providing guidance on levels of fire resistance to include in prescriptive documents covering a population of buildings meeting particular characteristics (especially use and height).

The use of time-equivalence methods has been discussed in detail by others (Cooke, 1999; Abu, Gerlich & Wade, 2013; Wade, Gerlich & Abu, 2014; Xie, Abu & Spearpoint, 2015). Similar concepts including energy dose methods and normalised heat load are described by Harmathy (1980), Kodur & Pakala (2010), Harada et al. (2000) and Wade et al. (2015). Inputs to time-equivalence methods include building parameters such as ceiling height, fuel load and material thermal property factors. The origins of the time-equivalence concept can be traced back to Ingberg (1928) who attempted to correlate the fuel load with an equivalent period of exposure in a standard fire resistance test. Law, Stern-Gottfried & Butterworth (2015) are critical of time-equivalence because it "enables an engineer to produce a solution (specifying a level of fire resistance) without directly considering the goals (how robust should the structure be?) or constraints (is a uniform fire in this space likely?) of the given building".

3.1 Previous New Zealand research

Cosgrove and Buchanan (1996) showed that a warehouse industrial building in New Zealand was likely to have at least one fire every 100 years. They reported that these buildings accounted for only 15% of all fires but represented up to 50% of the financial losses in fire.

Clifton and Forrest (1996) previously estimated the structural fire resistance for each of the fire hazard categories (FHC) used in the Acceptable Solution at the time (C3/AS1). They noted that the enclosure conditions of many single-storey industrial buildings differed from that typically assumed for other buildings:

- The S-rating provisions did not allow for any increase in horizontal roof openings during a fire resulting from roof distortion or collapse. They proposed that the effect of the increase in roof openings could be accounted for by assuming 20% horizontal opening when determining the S-rating.
- The thermal properties of all the bounding materials corresponded to concrete or dry wall construction rather than sheet steel. They proposed the calculated value of the time-equivalent fire severity be multiplied by a factor of 0.67 to represent the difference in the actual thermal inertia properties of a steel roof compared to that assumed.

Clifton and Forrest (1996) suggested that the difference in thermal properties would be more significant for the lower fire loads (FHC1) whereas the increased ventilation would be more significant for the higher fire loads (FHC3). They concluded that:

- for FHC 1, the structural fire severity would typically be 20–25 minutes
- for FHC 2, the structural fire severity would typically be 40–50 minutes
- for FHC 3, the structural fire severity would typically be 60–75 minutes
- for FHC 4, the structural fire severity would typically be more than 75 minutes.

They also recommended that, for FHC 4, if fire service intervention could be reasonably assumed, a fire resistance rating of 90 minutes should be used for fire loads up to 3000 MJ/m^2 or a fire resistance rating of 120 minutes for fire loads higher than 3000 MJ/m^2.

3.2 UK risk-based method for specifying FRR

A risk-based methodology was used to revise fire resistance ratings in BS 9999 and Approved Document B in the United Kingdom and is described in this section considering its potential application to New Zealand.

A Task Group to the BSI Committee FSH/14/-/2 was established to develop a new set of tables for inclusion in BS 9999:2008 based on a time-equivalent approach to quantifying fire severity. The approach is documented by Kirby et al. (2008) and Kirby, Newman & Butterworth (2004).

In order to develop a risk-based approach to establishing appropriate levels of fire resistance, it is necessary to define the acceptable risk. Ideally, this would be expressed in a quantitative form, for example, probability of 'some unacceptable event' less than y x 10^{-n}. However, acceptable risk can change with the perceived consequences. For example, society is much less accepting of multiple-fatality events compared to single-fatality incidents, or alternatively the collapse of a single-storey industrial or manufacturing building is more acceptable to society compared to a high-rise apartment building.

When specifying fire resistance ratings for different types of buildings, ideally the relative risks should be similar. In the UK methodology, it was assumed that the acceptable risk is constant and that a relative risk would be evaluated for different occupancies and building heights.

Kirby et al. (2008) set a baseline risk level applying to a building height of 18 m and the 80th percentile value from the fire resistance period cumulative frequency distribution curves for a given occupancy and calculated the acceptance criterion for the relative risk as follows. This height and fractile were justified on the basis that the 80th percentile was commonly used in fire safety design and that firefighters would be required to enter the building for search and rescue. However, it is questionable how applicable this would be to single-storey industrial buildings in New Zealand since fire occurrence is much more strongly correlated with floor area than building height as discussed later in this section.

Several assumptions were made regarding the frequency and consequence of fire:

- The frequency was mainly influenced by the size of the building of which building height was a reasonable measure.
- The consequence was also directly proportional to the building height – although Kirby et al. (2008) acknowledged that it was likely to depend on the failure mode.

A risk index (R) for the building was proposed as given in Eqn. 3-1 where $P_{occ}()$ is the frequency of fire occurrence, $P_{fail}()$ is the probability of failure and C is the consequence of failure (Law, Stern-Gottfried & Butterworth, 2015).

$$R = P_{occ}() \times P_{fail}() \times C \qquad \textbf{Eqn. 3-1}$$

Substituting $P_{occ}()$ and C with the building height h and with r as the required target reliability to prevent failure gives (Law, Stern-Gottfried & Butterworth 2015):

$$R = h \times P_{fail}() \times h \qquad \textbf{Eqn. 3-2}$$

$$R = (1 - r) \times h^2 \qquad \textbf{Eqn. 3-3}$$

It was stated that Eqn. 3-3 was calibrated against existing guidance in Approved Document B in the United Kingdom where it was found that, for 18 m building height, the 'accepted' reliability was 80%.

For a base case building of 18 m and a target reliability of 80%, the relative risk criterion used therefore was:

$$R = \left(1 - \frac{80}{100}\right) \times 18^2 = 64.8 \qquad \textbf{Eqn. 3-4}$$

The above relationship was used to determine what target reliability r (or fractile values of fire severity) should be used for other building heights to maintain the same relative risk. This can be determined by rearranging Eqn. 3-3.

$$r = 100\left(1 - \frac{R}{h^2}\right) = 100\left(1 - \frac{64.8}{h^2}\right) \qquad \textbf{Eqn. 3-5}$$

The percentile values adopted in BS 9999:2008 for different building height ranges are shown in Table 6 with an incremental consequence rating assigned to each height band. The relative risk criterion (64.8) is specific to the benchmarking against Approved Document B and may or may not be appropriate in other jurisdictions.

Table 6. Target reliability values adopted for BS 9999:2008 based on building height (Kirby, Newman & Butterworth, 2004).

Height (m)	Target Reliability Percentile (%)	Consequence rating	
0-5	20	1	Single storey buildings
5-11	46.4	2	Typically 2-3 storeys
11-**18**	**80**	3	Typically 3-5 storeys Base-line case for relative risk
18-30	92.8	4	Typically 5-6 storeys
30-60	98.2	5	Reasonably tall buildings
>60	99.6	6	Exceptionally tall buildings
****	100	7	

It was also considered that Table 6 should apply to buildings with similar evacuation characteristics corresponding to occupants who were alert and familiar with the building. Evacuation characteristics can be represented by the level of occupant familiarity with the building, their alertness (awake or asleep) and the type of evacuation procedure used (phased or simultaneous). Furthermore, it was thought that the degree of familiarity with the building while having some effect on the evacuation time should not affect the fire resistance period. It was also thought that a phased evacuation should not affect the fire resistance period since other fire protection requirements were included to compensate for the increased risk. However, if the occupancy was such that evacuation could not be relied upon or completed – for example, a medical care facility – an additional factor of safety would be needed, and this would be achieved by increasing the consequence rating in Table 6 by two categories.

Buildings containing any sleeping risk were also thought to require an additional factor of safety compared to a non-sleeping occupancy, and it was proposed that this would be achieved by increasing the consequence rating in Table 6 by one category.

In these cases, the target reliability value from Table 6 associated with the adjusted consequence rating would apply. Kirby et al. (2008) applied these target reliability values to their results and provided the following table (Table 7) of fire resistance times for a range of occupancies and consequence ratings.

Table 7. Time-equivalence outputs (in minutes) from the cumulative frequency distributions for non-sprinklered occupancies (Kirby et al. 2008).

Occupancy	Consequence rating						
	1	2	3	4	5	6	7
Dwelling	51	67	88	102	116	127	151
Hospital	<30	19	32	54	71	84	120
Hotel	<30	26	47	57	69	79	95
Office	<30	31	60	85	114	146	236
Retail	<30	38	68	95	131	174	241
Assembly (low)	<30	28	54	67	83	99	121
Assembly (med)	<30	45	74	99	130	162	240
Assembly (high)	<30	39	87	125	177	227	241
Manufacturing (low)	<30	28	64	88	118	143	151
Manufacturing (high)	58	103	183	241	280	293	300

Based on the analysis of Kirby et al. (2008), risk factors as shown in Table 8 were given in PD 6688-1-2:2007 *Background paper to the UK National Annex to BS EN 1991-1-2* (Annex B). These were intended to be applied to fire severity calculations using the time-equivalent formula in Annex F of BS EN 1991-1-2:2002 *Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire*. PD 6688-1-2:2007 was intended to replace BS EN 1991-1-2:2002 Annex F for the purpose of British Standards. These risk factors were developed so that the resultant fire resistance periods aligned with the fire resistance periods given in Approved Document B to the Building Regulations 2000 for the general case. These risk factors are distinguished by building height bands and occupancy/use. It is noted that no risk factors (other than a multiplier on the FLED to account for dependability of structural behaviour) have been explicitly proposed in New Zealand in relation to the prescriptive fire resistance ratings in C/ASx nor with the time-equivalent formula given in C/VM2, which should be reviewed.

Table 8. Height associated with multiplication risk factors (Table B2 of PD 6688-1-2:2007).

Occupancy	Height associated with multiplication risk factor					
	0.65	**1.00**	**1.35**	**2.00**	**2.65**	**3.30**
Residential (dwelling)	-	0-5 m	5-18 m	18-30 m	>30 m	-
Residential (institutional)	-	-	0-5 m	5-18 m	18-30 m	>30 m
Residential (other)	-	0-5 m	5-18 m	18-30 m	>30 m	-
Office	0-5 m	5-18 m	18-30	>30 m	-	-
Retail	0-5 m	5-18 m	18-30 m	>30 m	-	-
Assembly (high)	0-5 m	5-18 m	18-30 m	>30 m	-	-
Assembly (med)	0-5 m	5-18 m	18-30 m	>30 m	-	-
Assembly (low)	0-5 m	5-18 m	18-30 m	>30 m	-	-
Industrial (high)	0-5 m	5-18 m	18-30 m	>30 m	-	-
Industrial (low)	0-5 m	5-18 m	18-30 m	>30 m	-	-

Regarding the effect of fire sprinklers, the Eurocode approach is to use a multiplication factor of 0.61 applied to the characteristic fire load density per unit floor area when calculating the time-equivalent value. This factor was derived in a major European study referred to as the Natural Fire Safety Concept. The value of 0.61 is based on a probability of sprinklers failing to extinguish the fire of 0.02, a probability of there being a fully engulfed compartment fire over the life of the building (55 years) of 2.2 x 10^{-5} per m^2, a floor area of 1000 m^2 and a target failure probability of the structure of 7.23 x 10^{-5} over the life of the building corresponding to a structural reliability index of 3.8 (Schleich, 2005, Chapter 3).

The UK BSI committee that had the responsibility of preparing the draft National Annex to the Code has also adopted the same value for sprinklers as found in UK guidance PD 6688-1-2:2007.

Recognising that existing time equivalence methods do not adequately consider the fire safety goals and constraints of the building, Law, Stern-Gottfried & Butterworth (2015) proposed an alternative framework that adopts a risk-based approach for structural fire resistance and produced Table 9 where the unsprinklered design reliability in column 2 was determined from Eqn. 3-5. They also adopted a different approach to including the effect of sprinklers on the target design reliability, choosing a more explicit method as follows.

The contribution of sprinklers to the structural reliability can be expressed as follows, where r_T is the aggregate reliability of the structure, r_{sp} is the sprinkler reliability and r_{st} is the reliability of structure in the event of sprinkler failure (Law, Stern-Gottfried & Butterworth, 2015).

$$r_T = r_{sp} + (1 - r_{sp}) \times r_{st} \qquad \textbf{Eqn. 3-6}$$

Eqn. 3-6 was rearranged to determine the value for the required structural reliability from Eqn. 3-7 with values given in columns 3 to 5 of Table 9 for a given sprinkler reliability.

$$r_{st} = \frac{r_T - r_{sp}}{1 - r_{sp}} \qquad \textbf{Eqn. 3-7}$$

Table 9. Design structural reliability (Law, Stern-Gottfried & Butterworth, 2015).

Building height (m)	Design reliability	Structural reliability with:		
		75% reliable sprinklers	90% reliable sprinklers	95% reliable sprinklers
10	35%	N/A	N/A	N/A
20	84%	35%	N/A	N/A
30	93%	71%	28%	N/A
40	96%	84%	60%	19%
50	97%	90%	74%	48%
60	98%	93%	82%	64%
80	99%	96%	90%	80%

Table 9 implies that, if the desired aggregate reliability of the structure is less than the sprinkler reliability, structural fire protection may be omitted. However, Law et al. (2015) argue that, while this may be appropriate for some low-rise structures, it would not be acceptable in taller buildings since, if the sprinklers did not suppress the fire, failure of the structure would be inevitable.

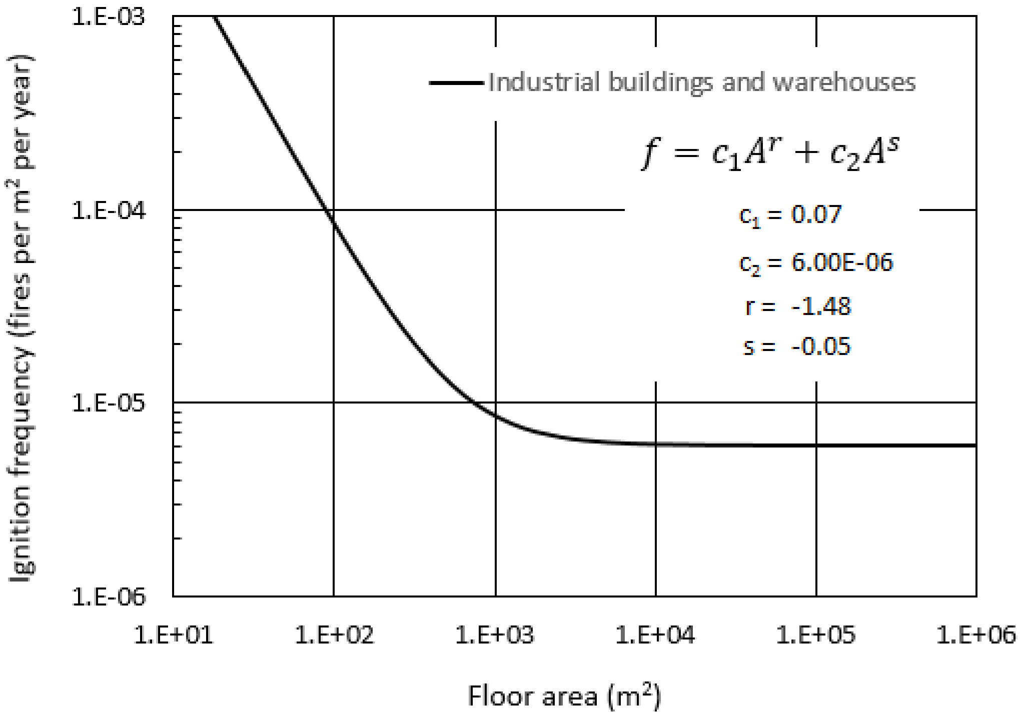
PD 7974-7:2003 *Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment* provides guidance on the reliability of sprinkler systems (BSI, 2003a). It provides the following values for the probability that a sprinkler system will operate successfully on demand. They state that these values assume no more than four sprinkler heads operate.

- Maximum: 95% (applicable to new systems in areas where statutory enforcement is in place).
- Typical: 90% (new life safety systems) or 80% (new property protection systems).
- Minimum: 75% (older systems).

In comparison for New Zealand, Gravestock (2008) recommended using a mean effectiveness of 90% for sprinkler systems in apartments and 95% for sprinkler systems in offices, with lower bounds ranging from 46% to 89% and upper bounds ranging from 97% to 99%. Frank et al. (2013) also estimated sprinkler system effectiveness based on New Zealand Fire Service data for the period 2001–2010 as 86% (mean) with a standard deviation of 4.6%.

There are a number of important simplifications and limitations that apply to the approach described above that should be pointed out. For example, the frequency of fire occurrence and consequence is assumed to be solely related to building height. However, Tillander and Keski-Rahkonen (2003) studied the ignition frequency of structural fires in Finland and showed that the ignition frequency varied with floor area and could be described by a Barrios model.

Figure 3 shows the relationship between ignition frequency and floor area for industrial buildings and warehouses relevant to the present study. Sandberg (2004) also determined the ignition frequency for different building types in Sweden for the years 2000–2002, giving the average ignition frequency for industrial buildings as 1.1E-05 fires per m^2 per year.



Adapted from Tillander and Keski-Rahkonen (2003).

Figure 3. Ignition frequency in industrial buildings and warehouses represented by a Barrios model fitted to data from Finland 1996–1999.

Hopkin (2017) reviewed the concept of fire resistance as a height-dependent metric for residential buildings. He found that the levels of risk for different apartment buildings of the same height varies substantially, concluding that, if a consistent level of risk is to be achieved, fire resistance must be specified in consideration of variables other than just building height. Regarding conventional structural fire resistance thresholds for tall single stair apartment buildings (in the UK typically limited to 120 minutes), he concluded that, in tall residential buildings, the reliability of the sprinkler system becomes increasingly important and extra resilience will likely be necessary.

The approach described by Kirby et al. (2008) determines a constant risk index applied to all building heights and is stated to be calibrated based on requirements for an 18 m high building. This leads to very low design fractile values (or target reliabilities) for single-storey buildings of only 20%, which seems contrary to normal engineering practice. However, it is acknowledged that target reliabilities should ultimately be set by the building regulator.

In the present study for single-storey industrial and warehouse buildings, we have extended the fire severity model based on the Eurocode 1 parametric time-temperatures curves along with the graphical time-equivalent method used by Kirby et al. (2008). Similarly, Latin hypercube sampling (LHS) methods are used to generate probability distributions for the fire severity accounting for the uncertainty in calculation inputs. However, determining a constant risk index and applying it to a range of building types and height has not been attempted here. The fire severity model and analysis methodology used is described in the next section.

4. Fire severity model

This section describes the fire severity model that is used in the subsequent analysis. The parametric time-temperature equations from EN 1991-1-2:2002 (CEN, 2002) were selected here as they have widespread use internationally. Alternative methods could also be considered for this type of analysis such as the simpler BFD curves developed by Barnett (2007) and Barnett and Clifton (2004).

4.1 Parametric time-temperature equations

4.1.1 Eurocode 1

EN 1991-1-2:2002 (CEN, 2002) states that the following temperature time equations are valid for compartments up to 500 m^2 with a maximum compartment height of 4 m and assumes that the compartment fire load will be completely burned out. The following equations are used in the analysis and include the modifications proposed by Reitgruber et al. (2006) where noted.

The time temperatures curves in the heating phase are given by:

$$\theta_g = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \quad \textit{Eqn. 4-1}$$

where θ_g is the gas temperature in the fire compartment, °C.

$$t^* = t\Gamma \quad \textit{Eqn. 4-2}$$

$$\Gamma = \left({}^{O}/_{b}\right)^2 / \left({}^{0.04}/_{1160}\right)^2 \quad \textit{Eqn. 4-3}$$

$$b = \sqrt{\rho c \lambda}\ 100 \leq b \leq 2200 \text{ Jm}^{-2}\text{s}^{-1/2}\text{K} \quad \textit{Eqn. 4-4}$$

$$O = A_v\sqrt{h_{eq}}/A_t\ \ 0.02 \leq O \leq 0.20 \text{ Jm}^{-2}\text{s}^{-1/2}\text{K} \quad \textit{Eqn. 4-5}$$

with,

t = time (hours)

ρ = density of the enclosure boundary (kgm^{-3})

c = specific heat of the enclosure boundary (Jkg^{-1}K^{-1})

λ = thermal conductivity of the enclosure boundary (Wm^{-1}K^{-1})

A_v = total area of vertical openings on all walls (m^2)

h_{eq} = weighted average of window heights on all walls (m)

A_t = total area of enclosure (walls, ceiling and floor including openings) (m^2)

The maximum temperature θ_{max} in the heating phase happens for $t^* = t^*_{max}$

$$t^*_{max} = t_{max}\Gamma \quad \textit{Eqn. 4-6}$$

with t_{max}= max $[0.14 \times 10^{-3} q_{t,d}/O;\ t_{lim}]$ ***Eqn. 4-7*** [1]

where,

$q_{t,d}$ = the design value of the fire load density related to the total surface area of the enclosure A_t whereby $q_{t,d} = q_{f,d} \times A_f/A_t$ with $50 \leq q_{t,d} \leq 1000$ MJm^{-2}

$q_{f,d}$ = the design value of the fire load density related to the surface area of the floor in MJm^{-2}

t_{lim} = 0.333 hr (20 min) assuming a medium fire growth rate (25 min for slow and 15 min for fast fire growth rates).

If t_{max}=t_{lim}, then the fire is assumed to be fuel-controlled, otherwise it is ventilation-controlled.

When t_{max}=t_{lim}, then Eqn. 4-8 is used instead of Eqn. 4-2.

$$t^* = t\Gamma_{lim} \qquad \textbf{Eqn. 4-8}$$

$$\Gamma_{lim} = \left({}^{O_{lim}}/_{b}\right)^2 / \left({}^{0.04}/_{1160}\right)^2 \qquad \textbf{Eqn. 4-9}$$

$$O_{lim} = 0.14 \times 10^{-3} q_{t,d}/t_{lim} \qquad \textbf{Eqn. 4-10}$$ [2]

If $O > 0.04$ and $q_{t,d} < 75$ and $b < 1160$, Γ_{lim} is multiplied by k.

$$k = 1 + \left(\frac{O - 0.04}{0.04}\right)\left(\frac{q_{t,d} - 75}{75}\right)\left(\frac{1160 - b}{1160}\right) \qquad \textbf{Eqn. 4-11}$$

The time temperature curves in the cooling phase are given by:

$$\theta_g = \theta_{max} - 625(t^* - t^*_{max}\, x) \text{ for } t^*_{max} \leq 0.5 \qquad \textbf{Eqn. 4-12}$$

$$\theta_g = \theta_{max} - 250(3 - t^*_{max})(t^* - t^*_{max}\, x) \text{ for } 0.5 < t^*_{max} < 2 \qquad \textbf{Eqn. 4-13}$$

$$\theta_g = \theta_{max} - 250(t^* - t^*_{max}\, x) \text{ for } t^*_{max} \geq 2 \qquad \textbf{Eqn. 4-14}$$

where t^* is given by Eqn. 4-2.

$$t^*_{max} = (0.14 \times 10^{-3} q_{t,d}/O)\ \Gamma \qquad \textbf{Eqn. 4-15}$$ [3]

$$x = 1 \text{ for } t_{max} > t_{lim}$$

$$x = t_{lim}\Gamma/t^*_{max} \text{ for } t_{max} = t_{lim}$$

[1] Coefficient 0.14×10^{-3} (instead of 0.2×10^{-3}) as suggested by Reitgruber et al. (2006).
[2] Coefficient 0.14×10^{-3} (instead of 0.1×10^{-3}) as suggested by Reitgruber et al. (2006).
[3] Coefficient 0.14×10^{-3} (instead of 0.2×10^{-3}) as suggested by Reitgruber et al. (2006).

4.1.2 Modifications to Eurocode 1

Suggested modifications were proposed by Reitgruber et al. (2006) in order to address a discontinuity in the parametric equations given in the Eurocode (CEN, 2002). This meant that a minor variation of the fire load or of the opening factor could lead to significantly different time-temperature curves. The discontinuity disappears if a single value is used for the coefficient in Eqn. 4-7 , Eqn. 4-10 and Eqn. 4-15 They found that the value for the coefficient that gave the best fit between the model and experiments based on around 50 experimental full-scale fire tests was 0.14×10^{-3}. This value for the coefficients has been used in the analysis described in this report. Reitgruber et al. (2006) also state that this coefficient should be used with the effective heat of combustion of wood taken as equal to 14 MJ/m² consistent with Eurocode 1 with a net calorific value of wood of 17.5 MJ/m² and a combustion factor of 0.8 (CEN, 2002).

A further change to the parametric equations given in the Eurocode (CEN, 2002) was made to incorporate the effects of roof ventilation. The method used was that described by Schleich (2005, Chapter 1) as follows:

Where horizontal (roof) openings are present, the opening factor given in Eqn. 4-5 is multiplied by a correction factor x_c given by the following equations and Figure 3.

$$x_c = (1 + 0.03(y - 1))y \qquad \textit{Eqn. 4-16}$$

$$y = 2\,(A_h h_h^{1/2})/(A_v h_{eq}^{1/2}) + 1 \qquad \textit{Eqn. 4-17}$$

In our analysis, we have assumed that the vertical openings are distributed centrally over the height of the wall (see Figure 4), which means that in Eqn. 4-17, $h_h = H/2$ where H is the height of the compartment (m).

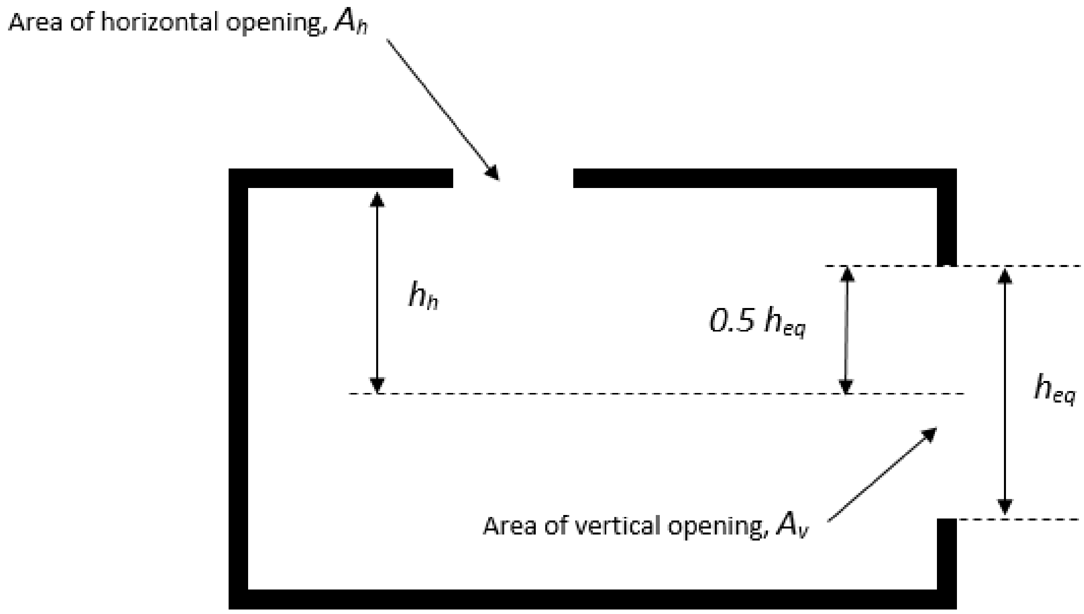


Figure 4. Vertical cross-section through enclosure with vertical and horizontal openings.

4.1.3 Roof failure/venting time

In this analysis, the roof venting is assumed to occur following failure of an unprotected steel roof support system. This approach is not likely to be highly accurate since roof venting depends on the type of construction of the roof, the presence of translucent panels or skylights and the type of purlins. However, for the type of analysis proposed here, it was considered to be reasonable.

The temperature rise (ΔT_s) of the unprotected steel section over a small time-step (Δt) is given by Buchanan & Abu (2017):

$$\Delta T_s = k_{sh}\frac{H_p}{A_s}\left(\frac{1}{\rho_s c_s}\right)\left[h_c\left(T_f - T_s\right) + \sigma\varepsilon\left(T_f^4 - T_s^4\right)\right]\Delta t \qquad \textbf{\textit{Eqn. 4-18}}$$

where,

T_f = temperature of the fire gases (K)

T_s = temperature of the steel section (K)

H_p = heated perimeter of the steel section (m)

A_s = cross-sectional area of the steel section (m^2)

c_s = specific heat of the steel section (540 $Jkg^{-1}K^{-1}$)

ρ_s = density of the steel section (7850 kgm^{-3})

h_c = convective heat transfer coefficient (35 $W\ m^{-2}\ K^{-1}$)

ε = resultant emissivity (0.7)

k_{sh} = correction factor for shadow effects (assumed 1 in this analysis)

Roof venting is assumed to occur when the temperature of the unprotected structural steel element reaches a critical temperature using equation Eqn. 4-19 (Buchanan & Abu 2017) where L_r is the load ratio.

$$T_{s,limit} = 950 - 690L_r \qquad \textbf{\textit{Eqn. 4-19}}$$

4.1.4 Fire gas temperature following roof venting

The fire gas temperature is calculated for two cases: 1) wall only ventilation and 2) wall and roof ventilation. The ventilation area in these two cases is assumed to be a constant from the start of each simulation as required by the parametric time-temperature equations.

Following roof failure, the fire gas temperature is assumed to follow the parametric curve based on both wall and roof ventilation. It would be unrealistic and non-conservative to assume a simple switchover from the wall only ventilation curve to the wall and roof ventilation curve following the calculated time for roof venting to commence. This is because the latter assumes that roof venting occurs from the start of the fire instead of from the time of switchover. This potentially results in a shorter fire duration compared to when venting occurs at a later time. Instead, a time-shift was introduced as illustrated in Figure 5 where the wall and roof venting curve was shifted to the right such that the intersection of the two curves occurred at the predicted time of roof venting. A 'combined' fire gas temperature curve is then defined, which is used as the boundary condition for determining the temperature of the protected steel element, which in turn is used for the fire severity (and fire resistance) calculation described in section 4.2. It is noted here that this approach could be quite conservative for cases where the predicted time of failure of the roof structure is long as the total quantity of fuel expended prior to failure would not be adequately accounted for. The methodology could be improved in this respect in the future.

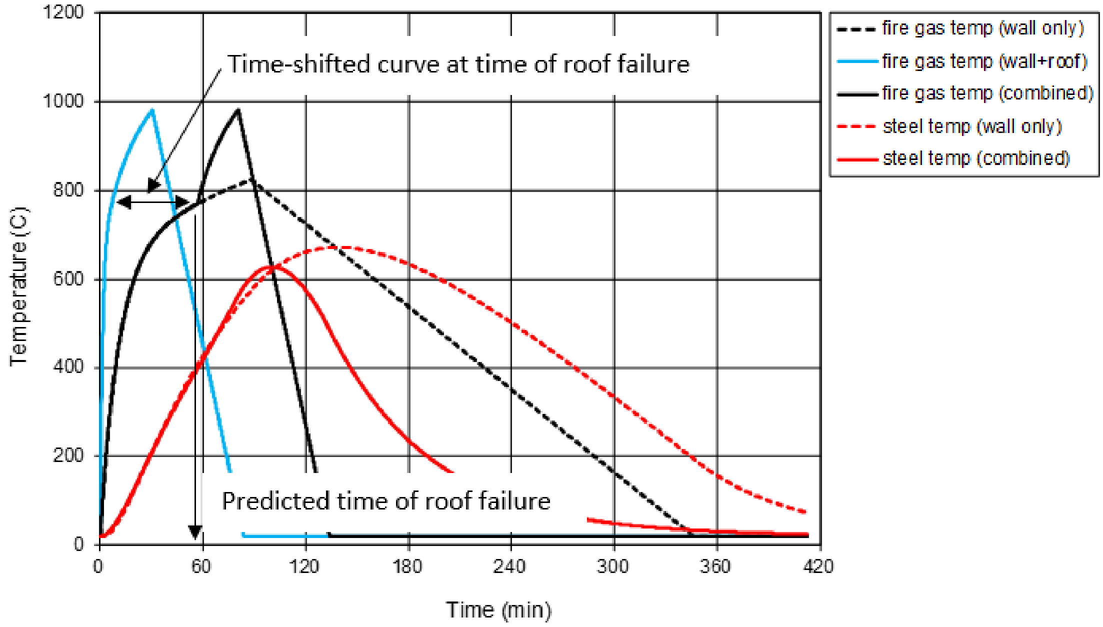


Figure 5. Constructing the combined fire gas temperature curve.

4.1.5 Validation and limitations

The parametric expressions have been validated against a large body of fire data from tests conducted in the United Kingdom by Corus Fire Engineering and the Fire Research Station (now BRE). In the majority of cases, an excellent correlation was achieved between the test data and the analytical calculations. In cases of poor correlations, predictions of the fire conditions were more onerous and thus the results were conservative. Figure 6 presents the agreement between the parametric equations in EN1991-1-2:2002 Annex A (CEN, 2002) against real fire tests. The correlation coefficient is noted as being 0.75 (Schleich, 2005).

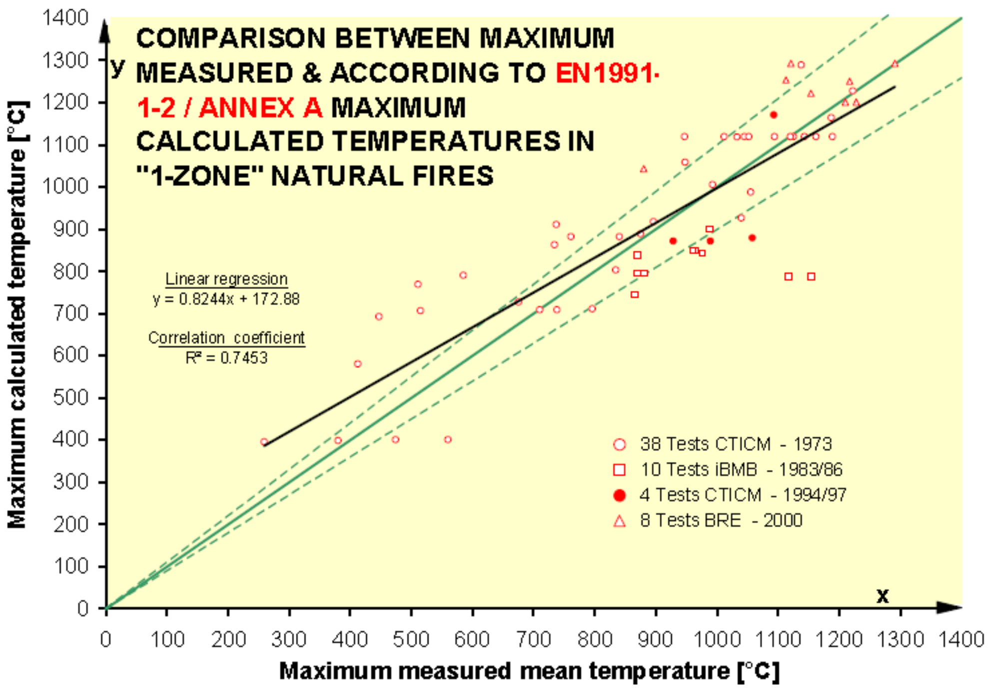


Figure 6. Parametric equations in EN1991-1-2:2002 compared to real fire tests (Schleich, 2005, Chapter 5)

Regarding the change in coefficient (to 0.14 × 10^{-3}) suggested by Reitgruber et al. (2006), they say that the coefficient has been calibrated in such a way that the model gives, on average, the same maximum temperature as the one observed in a series of about 50 experimental full-scale fire tests. Another way of looking at this coefficient is to compare it to the ventilation-limited heat release rate calculation by reformulating Eqn. 4-7 as:

$$t_{max} = 0.14 \times 10^{-3} q_{t,d} \Big/ O = \frac{q_{f,d} * \frac{A_f}{A_t}}{7143 A_v \sqrt{h_{eq}} / A_t} \qquad \textit{Eqn. 4-20}$$

$$t_{max} = \frac{q_{f,d} * A_f}{7143 A_v \sqrt{h_{eq}}} \qquad \textit{Eqn. 4-21}$$

The ventilation-limited heat release rate applying Kawagoe's (1958) equation is:

$$HRR_{vent,lim} = \left(1.5 \frac{\mathrm{MJ}}{\mathrm{s}}\right) A_v \sqrt{h_{eq}} = \left(5400 \frac{\mathrm{MJ}}{\mathrm{h}}\right) A_v \sqrt{h_{eq}} \qquad \textit{Eqn. 4-22}$$

By neglecting the initial growth period and assuming a constant heat release rate, the total heat release rate is:

$$HRR_{total} = \frac{7143}{5400} HRR_{vent,lim} = 1.32 * HRR_{vent,lim} \qquad \textit{Eqn. 4-23}$$

This is comparable to the C/VM2 peak heat release rate assumption of 1.5 times the ventilation-limited heat release rate. It takes into consideration the observation that some flaming typically takes place outside the compartment. The 0.2 × 10^{-3} coefficient in EN 1991-1-2:2002 for Eqn. 4-7 , Eqn. 4-10 and Eqn. 4-15 drops the assumed constant heat release rate to just below the ventilation-limited heat release rate, which would provide slightly more conservative burnout times but be less realistic based on observed fire behaviour. Incidentally, it has been observed experimentally that wood cribs do not burn more than 30–40% fuel rich, with Babrauskas (2016) reporting an upper limit of approximately 37% fuel rich giving a very similar ratio of 1.37. Frank et al. (2018) also determined a ratio of 1.35 in a reduced-scale enclosure experiment burning wood cribs.

PD 6688-1-2:2007 section 3.1.2 (BSI, 2007) has the following additional commentary on the EN 1991-1-2:2002 parametric equations.

> Non-contradictory complementary information
>
> BS EN 1991-1-2:2002, Annex A may be used with the following complementary information.
>
> a) The calculations may also be applied to fire compartments greater than 500 m^2.
>
> b) The application of the parametric fire may be extended to compartment heights greater than 4 m. However, for tall compartments, the outputs may be particularly onerous and it may be more appropriate to consider using computational fluid dynamics or other similar calculation methods.
>
> c) The insulation factor b for the compartment boundaries assumes ambient temperature properties. Elevated temperature values may be used where appropriate reliable data is available.
>
> d) The lower limit of the range of opening factors may be extended from 0,02 $m^{1/2}$ to 0,01 $m^{1/2.}$ This broadening of the scope of application of the parametric fires was based on a major calibration/research exercise [1] leading up to the development of the NA to BS EN 1991-1-2. The following is worth noting.
>
> 1) Sensitivity analysis was carried out on the effect of increasing the floor areas.
>
> 2) The 0.01 factor was based upon historical data and calibration against previous analytical studies.
>
> 3) It was demonstrated that by increasing the compartment height the temperature time history of the fires would result in lower temperature (less severe heating curve). This is because the fire load is expressed as a function of the floor area.

PD 6688-1-2:2007 section 3.1.2 (BSI, 2007) noted that the parametric equations can be applied to floor areas greater than 500 m^2. However, it is noted here that, in some of these cases, the uniform fire assumption may not be the critical or worse case. Localised heating conditions or travelling fires could be more severe (Stern-Gottfried et al., 2010). This has not been accounted for in this research.

4.2 Fire severity measures

Two separate methods for describing fire severity are used in this study, and each results in an equivalent time t_e. This is commonly interpreted as the level of fire resistance required by an element sufficient to withstand a full burnout of the natural fire. In this study, the equivalent time is taken as the basis for selecting an appropriate level of fire resistance given knowledge of the time temperature history of a natural fire. Two approaches are used in this research as described next, but alternative methods are also possible such as the minimum load capacity method (Xie, Abu & Spearpoint, 2015).

4.2.1 Graphical method for a protected steel section

This approach uses the maximum temperature reached by a protected steel section as a suitable metric for fire severity. The maximum steel temperature reached when subjected to the full duration of a natural fire is calculated, and the time taken to reach this same maximum temperature in a standard fire resistance test is determined. This time is called the equivalent time t_e.

The maximum temperature reached is not necessarily indicative of structural performance. The premise is that burnout of the natural fire can occur without structural failure if the element has been shown to successfully withstand the standard furnace test for at least the equivalent time period. Although time-equivalence is often associated with structural performance (of protected steel members), the concept has been developed based on temperature measurement of a narrow range of unloaded protected steel members (Wade, Gerlich & Abu, 2014).

The same calculation procedure can be used for both the natural fire and the standard time-temperature curve with the appropriate thermal boundary conditions in each case. Figure 7 shows a graphical representation of this method.

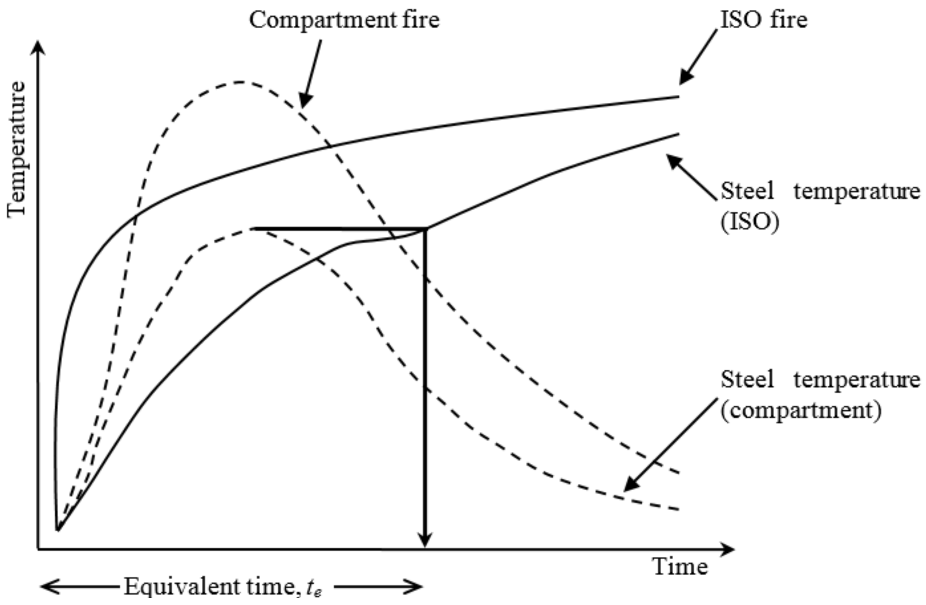


Figure 7. Graphical time-equivalence (Abu, Gerlich & Wade, 2013).

An iterative calculation method for determining the temperature of the protected steelwork is used (Buchanan & Abu, 2017). The steel section is treated as a lumped mass at a uniform temperature. It is assumed the external surface of the protection material is at the same temperature as the fire gases. It is also assumed the internal surface of the protection material is the same temperature as the steel section. The temperature rise (ΔT_s) of the steel section over a small time-step (Δt) is given by:

$$\Delta T_s = \frac{H_p}{A_s}\left(\frac{k_i}{d_i \rho_s c_s}\right)\left[\frac{(T_f - T_s)}{(1+\phi/3)}\right]\Delta t - \left(e^{\phi/10} - 1\right)\Delta T_f \qquad \textit{Eqn. 4-24}$$

$$\phi = \frac{\rho_i c_i}{\rho_s c_s} d_i \frac{H_p}{A_s}$$

where,

T_f = temperature of the fire gases (K)

T_s = temperature of the steel section (K)

H_p = heated perimeter of the steel section (m)

A_s = cross-sectional area of the steel section (m^2)

c_s = specific heat of the steel section (540 $Jkg^{-1}K^{-1}$)

ρ_s = density of the steel section (7850 kgm^{-3})

k_i = thermal conductivity of the protection material (0.1 $Wm^{-1}K^{-1}$)

c_i = specific heat of the protection material (1200 $Jkg^{-1}K^{-1}$)

ρ_i = density of the protection material (550 kgm^{-3})

d_i = thickness of the protection material (m)

The maximum time step in minutes is given from Gamble (1989):

$$\Delta t \leq \frac{3.25\rho_s H_p}{60A_s} \approx \frac{25000\, H_p}{60A_s} \qquad \textit{Eqn. 4-25}$$

A time step of 5 s was used in the analysis, which is valid for the range of H_p/A_s considered.

4.2.2 Cumulative radiant energy dose

An alternative approach compares the cumulative radiant energy (CRE) to which an element is exposed to in a natural fire with the time to reach this same energy dose in a standard fire resistance test. Nyman et al. (2008) used this method to predict integrity failure of a rated non-loadbearing lightweight wall in a compartment fire experiment. This method simply considers the emissive power of fire gases, ignoring the heat transfer within the element.

The cumulative radiant energy dose is the area under a plot of radiant energy versus time, expressed as:

$$E = \int_0^t \dot{Q}'' dt = \varepsilon\sigma \int_0^t \left(T_f{}^4\right) dt \qquad \textbf{\textit{Eqn. 4-26}}$$

where:

E = cumulative radiant energy on the assembly over a period of time (Jm^{-2})

$\dot{Q}''$ = radiant heat flux incident upon the assembly at any point in time (Wm^{-2})

5. Analysis procedure

The analysis carried out uses the Eurocode parametric time-temperature equations (CEN, 2002) with some modifications following recommendations by Kirby (2004), Corus Fire Engineering (2006) and PD 6688-1-2 (BSI, 2007), changes to coefficients (Reitgruber et al., 2006) and inclusion of roof openings (Schleich, 2005).

These were the steps followed:

- Decide on thermal properties for the compartment. A lightweight steel roof was assumed with the insulation factor b = 2200 J/(m^2 $s^{1/2}$ K) for the compartment boundaries. This is the upper end of the stated valid range of 100–2200 J/(m^2 $s^{1/2}$ K) for the parametric time temperature equations. C/VM2 requires 2500 J/(m^2 $s^{1/2}$ K) for this case as used in time equivalence formula but the difference is not considered to be significant. Elevated temperature values may be used where appropriate reliable data is available (Corus Fire Engineering, 2006) but were not in this study.
- Sample the firecell height assuming a uniform distribution (see section 5.2.1).
- Sample the floor area assuming a log-logistic distribution with sampled values in the range 50–200,000 m^2 (see section 5.2.2).
- Sample the wall opening heights as a proportion of the firecell height in the range 30–80%. Wall openings were assumed to be centred over the height of the wall.
- Sample the wall opening area from a uniform distribution in the range 2.5–20% of the floor area (see section 5.2.3).
- Sample the FLED from a cumulative frequency distribution for industrial and warehouse occupancies (see section 5.2.4).
- Sample H_p/A of the steel section in the range 140–280 m^{-1} assuming a triangular distribution with a peak at 240 m^{-1}. The basis for selection is given in section 5.2.5.
- Sample the load ratio for the unprotected steel element in the range 0.1–0.5 and calculate a critical steel temperature for failure.
- Sample the roof opening area from a uniform distribution in the range 2.5–20% of the floor area (see section 5.2.3).
- The combined opening factor for wall and roof openings is constrained to be in the range 0.01–0.2 $m^{1/2}$. In this analysis, this meant that, where the sampled values resulted in a combined opening factor greater than 0.2, then a value of 0.2 was used in the simulation. Similarly, if the sampled values were less than 0.01, then a value of 0.01 was used in the simulation.
- Calculate failure time for the unprotected steel element and assume roof ventilation occurs only after this time. The permitted lower limit of the combined opening factor range is 0.01 $m^{1/2}$ – this is less than the 0.02 $m^{1/2}$ in the Eurocode.
- The method for deriving the resulting fire gas temperature history incorporating a time-dependent roof venting was described in section 4.1.4.
- Sample the steel protection thickness in the range 10–30 mm assuming a uniform distribution.
- The calculations were done in an Excel spreadsheet. This included the predicted time-temperature history from the parametric equations and the predicted maximum steel temperature of a protected steel element from a one-dimensional heat transfer calculation. Steel and steel protection thermal properties were fixed.
- Determine the graphical time-equivalent value for the protected steel section.
- Alternative time-equivalence measure – determine the total cumulative incident energy to the wall over the duration of the fire 'burnout' and determine the

'equivalent time' in the standard fire resistance test that would result in this amount of energy.
- Simulations are performed using a LHS technique with @RISK add-in for Microsoft Excel 2017 version 5.3.2. The convergence tolerance used was 1% with a 95% confidence interval or better with tests performed on the simulated mean and the 80th percentile every 250 intervals. This typically resulted in up to 50,000 simulations per case analysed.
- Construct cumulative frequency distribution plots for t-e (for the two different approaches).

Monte Carlo sampling techniques are entirely random, with any given sample value falling anywhere within the range of the input distribution. However, the LHS method stratifies the input probability distributions. With this method, @RISK divides the cumulative frequency distribution curve into equal intervals on the cumulative probability scale, then takes a random value from each interval of the input distribution. This means that, even for modest numbers of iterations, the LHS method makes all or nearly all sample means fall within a small fraction of the standard error. Therefore, the LHS method makes simulations converge faster than Monte Carlo.

It is noted that uniform burning across the entire floor area does not occur in large floor area compartments – rather, travelling or migrating fires are likely to occur (Stern-Gottfried & Rein, 2012). Therefore, while the parametric equations are not sensitive to increasing the area above 500 m^2, there is an underlying limitation on the applicability of the parametric equations, which may not be representative of the exposure in a much larger compartment. This is beyond the scope of this research and is a limitation of the analysis, but including travelling fires in the methodology as proposed by Stern-Gottfried and Rein (2012) could be an avenue for further investigation. However, it would be difficult to account for the beneficial effect of roof venting in conjunction with a travelling fire scenario.

Five cases were established for the subsequent analysis, and these are summarised in Table 10. All cases represented non-storage or storage up to 3 m, except Case C, which was intended to represent buildings where storage above 3 m is present.

Table 10. Summary of cases analysed.

Case	Firecell height	Design fire load MJ/m^2-floor area (80th percentile value)
A	2.7–4.0 m	PD 7974-1:2003 470 MJ/m^2 (non-storage)
B	3.5–6.0 m	PD 7974-1:2003 1800 MJ/m^2 (storage up to 3 m)
C	4.0–8.0 m	VM2 800 MJ/m/m^2 (storage above 3 m)
D	2.7–6.0 m	VM2 800 MJ/m^2
E	2.7–6.0 m	VM2 1200 MJ/m^2

5.1 Known inputs

The fire compartment is assumed to be constructed with lightweight steel roof and wall boundaries with a thermal inertia of 2200 J m^{-1} s$^{-0.5}$ K^{-1}. A square compartment with a flat roof is assumed with equal length and width and uniform height.

When determining the maximum temperature in the heating phase, a medium fire growth rate (t_{lim} = 20 min) is assumed in Eqn. 4-7 . Steel properties and steel protection thermal properties are given in section 4.2.1.

5.2 Uncertain input parameters

5.2.1 Firecell height

The following distributions for firecell height have been assumed in the analysis.

- Uniformly distributed in the range 2.7–4.5 m for non-storage occupancies.
- Uniformly distributed in the range 3.5–6.0 m for storage up to 3 m.
- Uniformly distributed in the range 4.0–8.0 m for a storage height above 3 m.

For a given fire load density based on floor area, increasing the height of a compartment will increase the surface area of the wall over which heat is lost. This means that tall compartments will typically result in lower fire gas temperatures than compartments of lesser height. Reasonable upper limits are applied here such that, if they were exceeded, the actual gas temperatures would not be expected to be any higher.

5.2.2 Floor area

Quotable Value New Zealand (QV) maintain a database of building property information. Wade & Page (2006) reported that QV have six categories of industrial building: heavy manufacturing (~1000 buildings), light manufacturing (~13,000 buildings), noxious (~300 buildings), service industries (~12,000 buildings), warehouses (~7000 buildings) and other (mainly multi-use, ~4000 buildings). The entire dataset comprised 40,275 buildings, with a total of 40,064,966 m² of floor area. Since the focus is on manufacturing and storage occupancies in this study, service industries were excluded, with Figure 8 showing the floor area distribution for this subset. The total number of buildings in this group is 27,273. The average floor area per building is taken as 995 m². More recent data from QV was not available and hence building stock data pre-2006 has been used in this study.

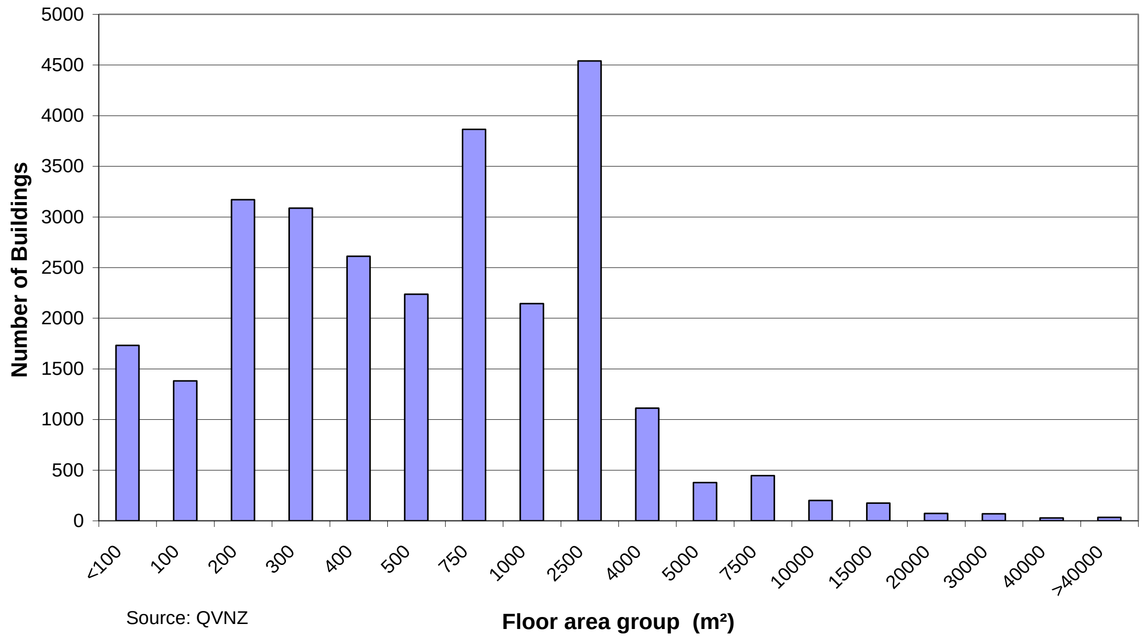


Figure 8. All industrial buildings (excluding service industries) – numbers by floor area (Wade & Page, 2006).

Figure 9 shows a graph of the cumulative frequency distribution for the building floor area. The QV data points (blue dots) and a log-logistic density function to best fit the QV data are shown. The log-logistic density function has a location parameter gamma of 0.05, shape parameter alpha of 1.2273 and scale parameter beta of 0.40951.

For the simulations, the sampled log-logistic distribution was truncated at the extreme ends such that only buildings with a floor area in the range 50–200,000 m² were simulated. The data showed that 95% of all buildings of this type in New Zealand have a floor area less than 3895 m².

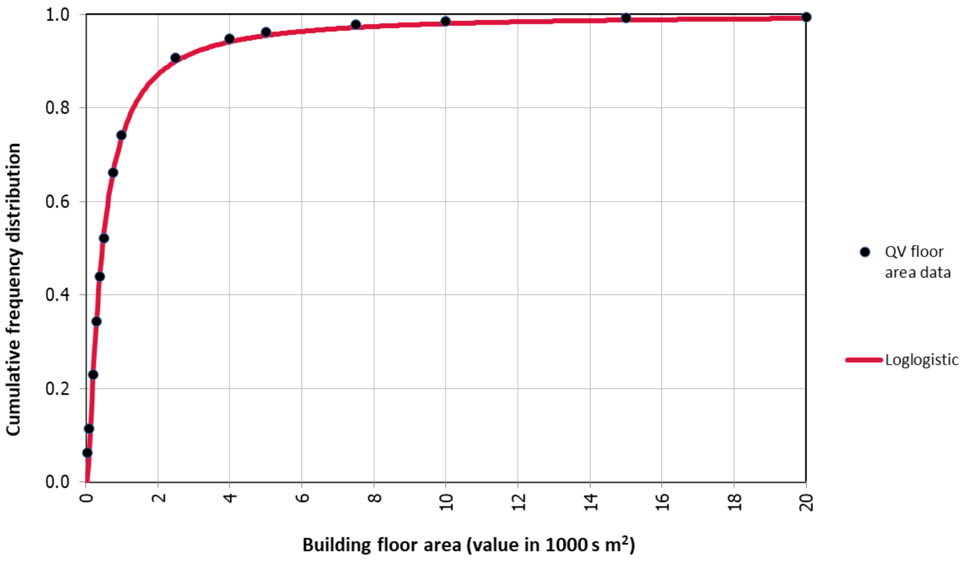


Figure 9. Cumulative frequency distribution for the building floor area (Wade & Page, 2006).

5.2.3 Ventilation

It is appreciated that ventilation can vary greatly depending on the building design and floor plan layout as well as changing during the course of fire development. Following the inputs adopted by Kirby et al. (2008) for manufacturing and storage occupancies, the wall opening height for ventilation is specified as a proportion of the firecell height assumed to be uniformly distributed in the range 30–80%. The area of wall openings is specified as a proportion of the floor area and is assumed to be uniformly distributed in the range 2.5–20%.

In the case of roof openings, which were not considered by Kirby et al, (2008), in the absence of any other data, the area of roof openings is also specified as a proportion of the floor area and is also assumed to be uniformly distributed in the range 2.5–20%, the same range as for the wall openings.

A combined wall and roof opening factor was determined from Eqn. 4-5 and Eqn. 4-16.

5.2.4 Fire load

The fire load distributions for Case A and B were taken from PD 7974-1:2003 *Application of fire safety engineering principles to the design of buildings – Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)* for manufacturing occupancies and manufacturing and storage occupancies respectively, whereas Cases C, D and E were based on C/VM2 guidance. The shape of the cumulative frequency distribution was based on the approach used by Kirby et al. (2008). The cumulative frequency distributions assumed for each case are summarised in Table 11.

Table 11. Summary of fire load cumulative frequency distribution used in analysis for each case.

	Occupancy	50% † MJ/m²	80% MJ/m²	90% MJ/m²	95% MJ/m²	100% MJ/m²
Case A	PD 7974-1:2003 manufacturing	300	470	590	720	
Case B	PD 7974-1:2003 Manufacturing & storage (up to 150 kg/m²)	1180	1800	2240	2690	3700
Case C	C/VM2 storage*	524 per m of storage height	800 per m of storage height	995 per m of storage height	1195 per m of storage height	1644 per m of storage height
Case D	C/VM2 *	524	800	995	1195	1644
Case E	C/VM2 *	787	1200	1493	1793	2467
Parameter ratio when normalised by 80th percentile (for Case B–E)		0.655	1.0	1.24	1.49	2.06

* Assumed shape of cumulative frequency distribution follows Case B.
† This is presented in PD 7974-1:2003 as an average, which may differ slightly from the 50th percentile (median).

Case B is stated as applicable for a combustible load up to 150 kg/m². Assuming a heat of combustion of 16 MJ/kg, this would represent a fire load of 2400 MJ/m². If the C/VM2 value of 800 MJ/m² per m of storage height was also used, then Case B would apply to a maximum 3 m storage height.

For storage buildings (Case C), the 80th percentile FLED is calculated using the C/VM2 design FLED of 800 MJ/m² per m of storage height (=800 x H_s); the 50th percentage given by 0.655 x 800 x H_s; the 100th percentage is 2.06 x 800 x H_s, where H_s is the nominal storage height in m (MBIE, 2014b). These factors are derived from the PD 7974-1:2003 cumulative frequency distribution and normalised by the 80th percentile as shown in the last row of Table 11.

For occupancies with storage height above 3 m, the storage height is set to a value 1 m below the sampled firecell height.

5.2.5 Steel section parameters

The ratio of the heated perimeter to the cross-section area (Hp/A) of the steel element of the steel section was in the range 140–280 m^{-1}, assuming a triangular distribution as used by Kirby, Newman & Butterworth (2004) with a peak at 240 m^{-1}. This range was selected based on a structural steel portal frame element (360UB45) that might be typical for a light-industrial building with light steel roof cladding (Liu, 2018).[4]

For the calculation of the protected steel temperature, the thickness of the steel protection material was assumed to be in the range 10–30 mm with a uniform distribution. The assumed thermal properties of the steel and of the protection material are given in section 4.2.1. The thermal properties of the protection material were representative of a sprayed vermiculite cement.

[4] A. Liu, BRANZ, personal communication, 2018.

6. Results

Results are generally filtered to remove iterations that were outside the valid ranges for fire load energy density (FLED) i.e. the valid range for fire load energy per square metre of enclosure surface area was 50 – 1000 MJ/m^2.

Where the combined opening factor for vertical and horizontal openings was calculated to be outside the valid range 0.01 to 0.2, the value used was capped at either the upper or lower bound as applicable and then used in the subsequent calculations. This was considered to be a conservative approach with respect to determining the gas temperatures in the enclosure.

6.1 Case A – no storage (PD 7974-1:2003)

The upper 80th percentile value for the fire load (MJ per m^2 floor area value) was 470 MJ/m^2 corresponding to the manufacturing occupancy in PD 7974-1 Table A.8 (BSI, 2003b). The proportion of the simulations resulting in the fire load (per unit surface area) being outside the stated limits of applicability in the parametric equations was (7739/34000 = 22.8 %). The filtered iterations were those below the low end of the valid fire load range as shown in Figure 10 such that the actual 80th percentile value increased from 470 to 525 MJ/m^2 after filtering as shown in Figure 11 and Figure 12.

The upper 80th percentile value for the calculated fire severity based on the graphical time-equivalent method was 45 min as shown in Figure 13. If the results are filtered to exclude the out-of-range simulations, the upper 80th percentile value for the calculated fire increases to 49 min as shown in Figure 14. The upper 80th percentile value for the calculated fire severity based on the CRE method was 43 min as shown in Figure 15. Using the CRE method in the analysis resulted in a slightly lower and less conservative calculation of the fire severity compared to the graphical time-equivalent method.

Roof venting was predicted to occur in 24% (8140/34000) of the simulations, and for these, the median time of roof failure was 19.3 min with a mode of 19.7 min.

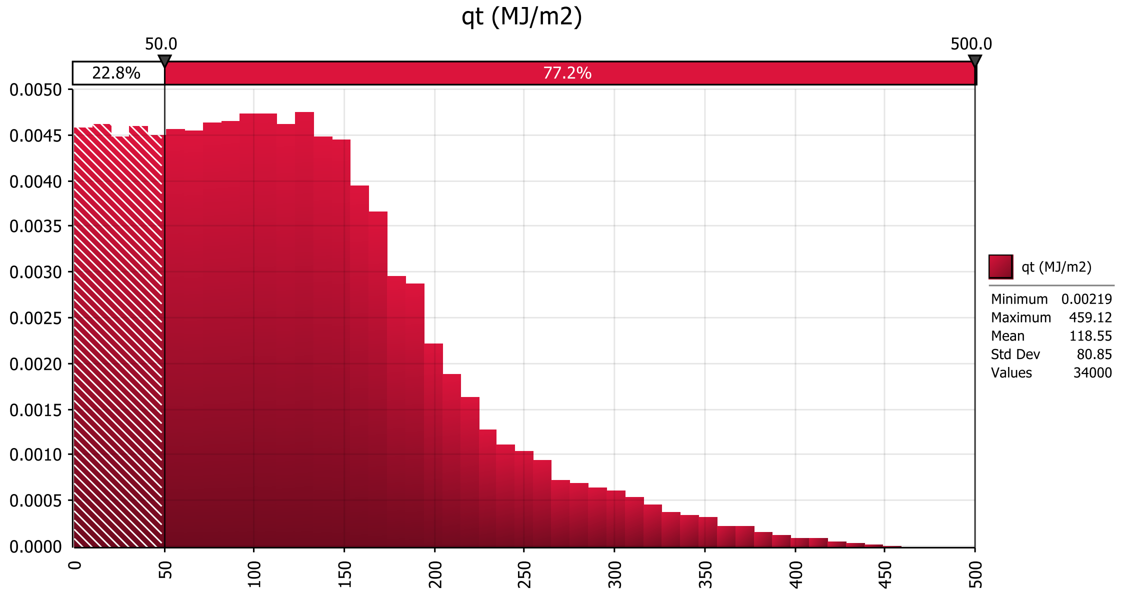


Figure 10. Case A probability density function for fire load per unit surface area showing limits of valid range.

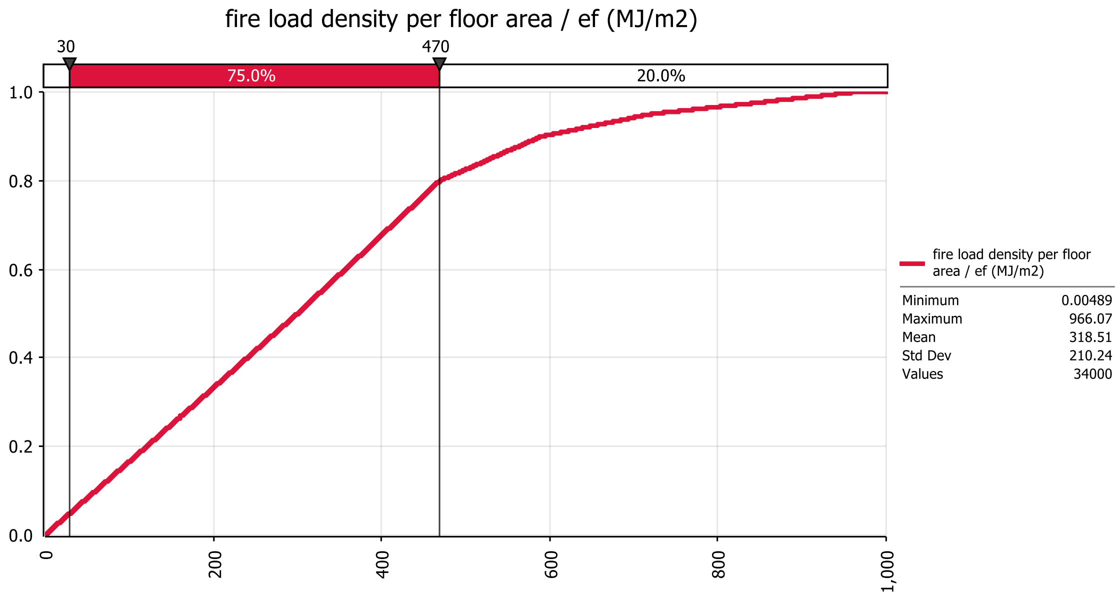


Figure 11. Case A ascending cumulative density function for the fire load energy density per unit floor area (unfiltered).

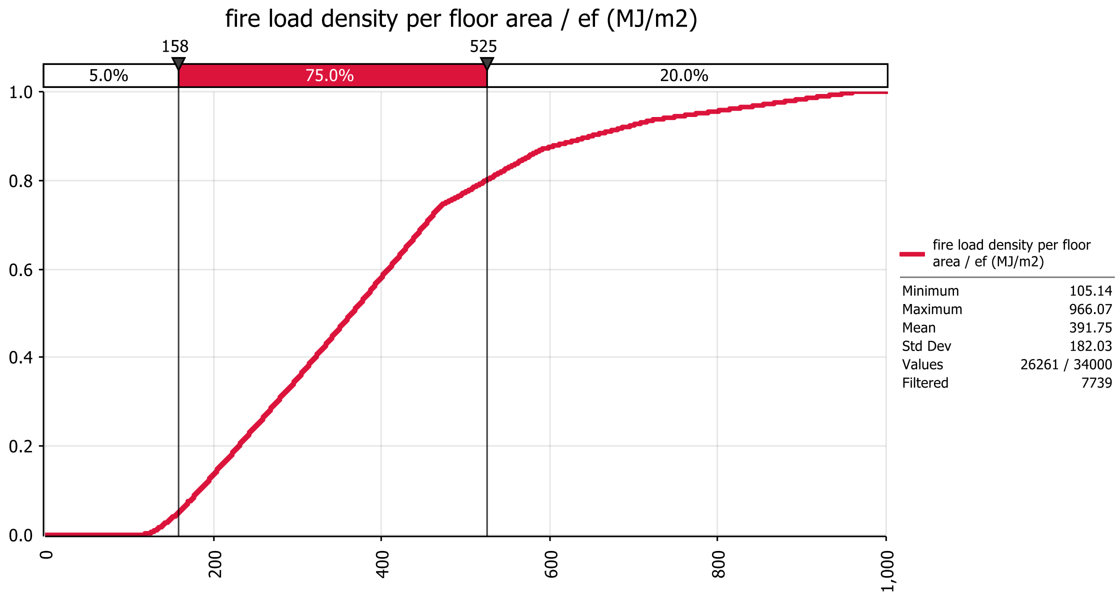


Figure 12. Case A ascending cumulative frequency distribution for the fire load energy density per unit floor area (filtered).

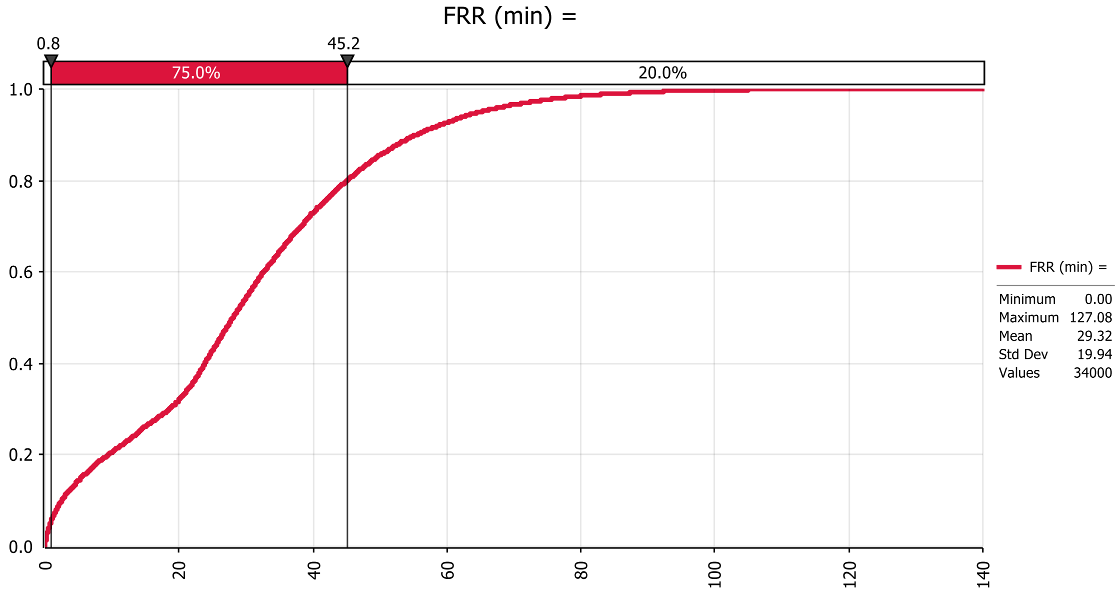


Figure 13. Case A ascending cumulative frequency distribution for FRR based on graphical t-e (unfiltered).

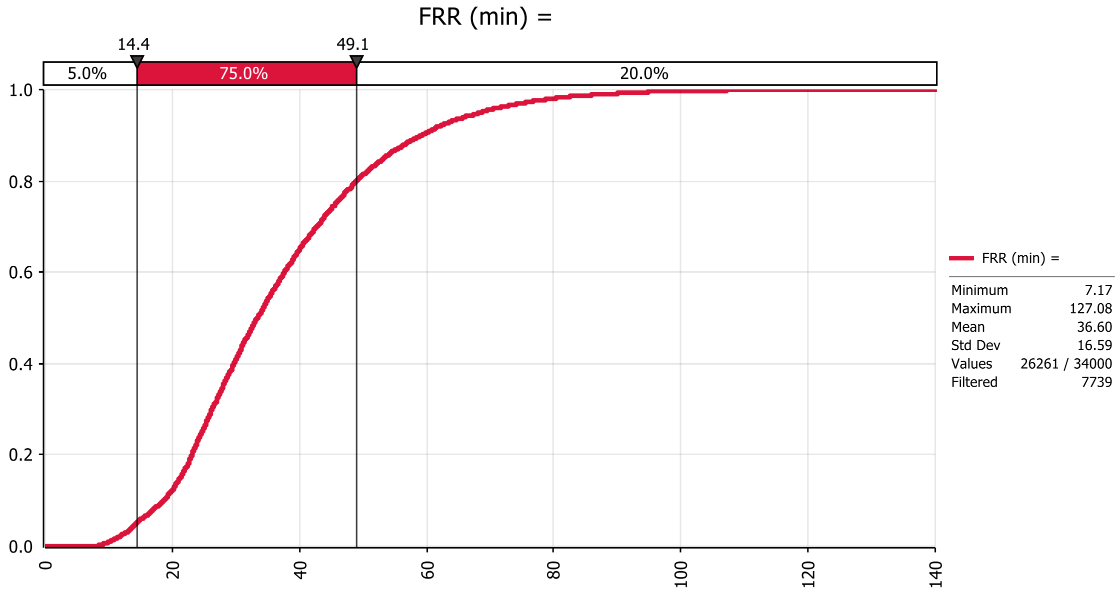


Figure 14. Case A ascending cumulative frequency distribution for FRR based on graphical t-e (filtered).

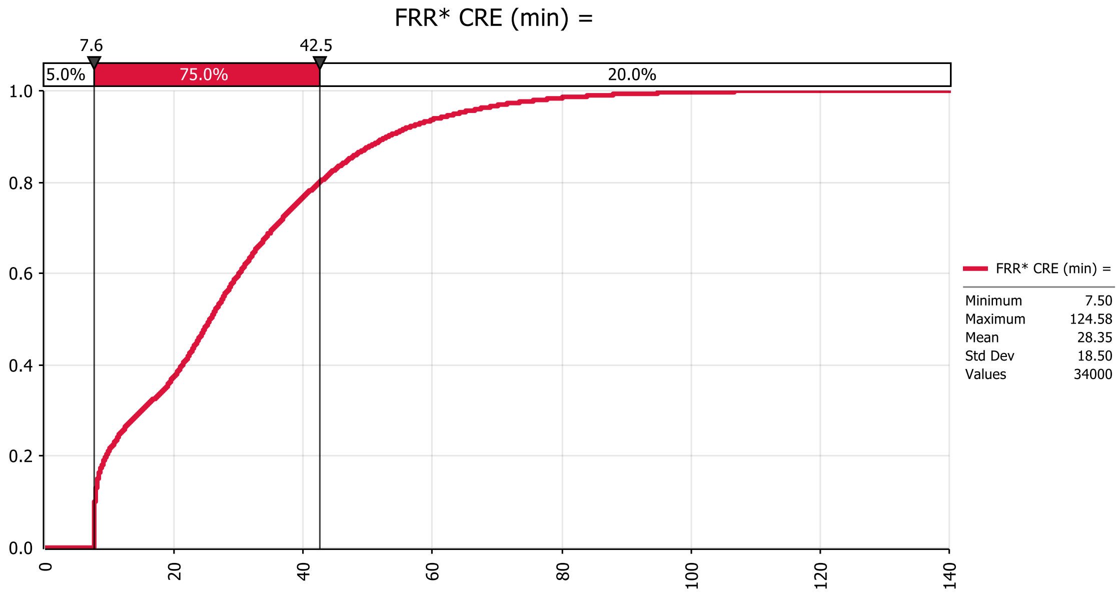


Figure 15. Case A ascending cumulative frequency distribution for FRR based on CRE method (filtered).

Figure 16 is a tornado plot demonstrating the sampled input parameter having the greatest effect on the output mean value of FRR based on graphical t-e. The fire load energy density had the greatest effect followed by the area of the wall openings as a percentage of the floor area, steel protection thickness and the load ratio.

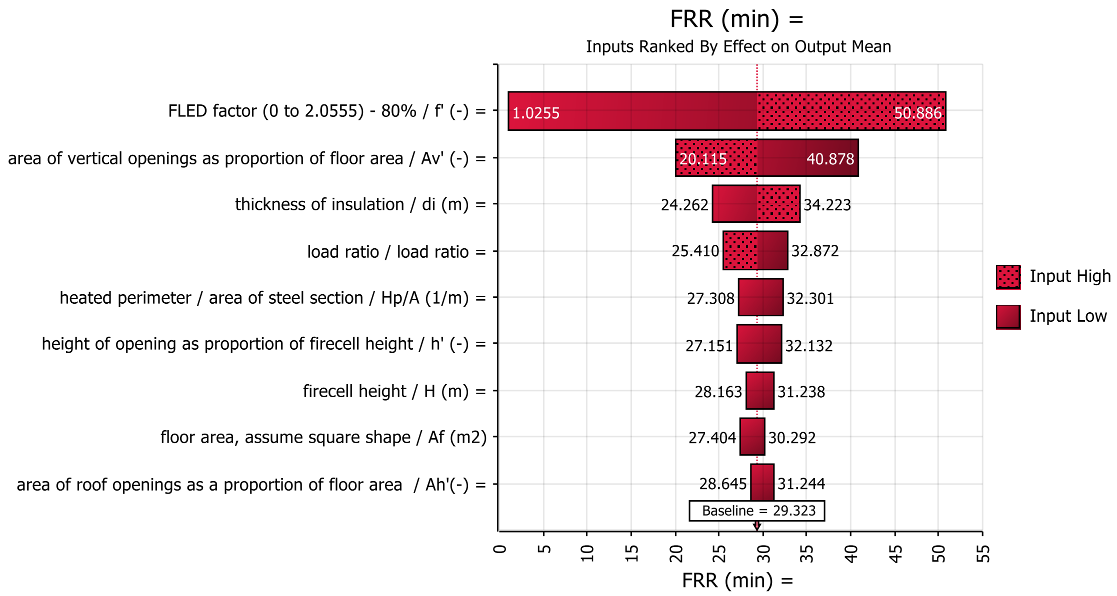


Figure 16. Case A tornado chart (change in output mean) for FRR based on graphical t-e (filtered).

6.2 Case B – storage up to 3 m

The design fire load MJ per m^2 floor area (80th percentile value) as 1800 MJ/m^2 for Case B, with assuming storage of combustibles less than 150 kg/m^2 (Table A8 of PD 7974-1:2003).

The proportion of the simulations resulting in the fire load being outside the stated limits of applicability of the parametric equations was (5521/50000 = 11.0%). Figure 17 shows that 4.6% of the simulations had a sampled fire load energy density value above the upper limit of 1000 MJ/m^2-surface area.

The upper 80th percentile value for the calculated fire severity based on the graphical time-equivalent method was 83 min as shown in Figure 18. If the results are filtered to exclude the out-of-range simulations, the upper 80th percentile value for the calculated fire falls to 80 min as shown in Figure 19. The upper 80th percentile value for the calculated fire severity based on the CRE method was 86 min as shown in Figure 20. Using the CRE method in the analysis resulted in a higher and more conservative calculation of the fire severity.

Roof venting was predicted to occur in 71% (35736/50000) of the simulations, and for these, the median time of roof failure was 20.9 min with a mode of 13.8 min.

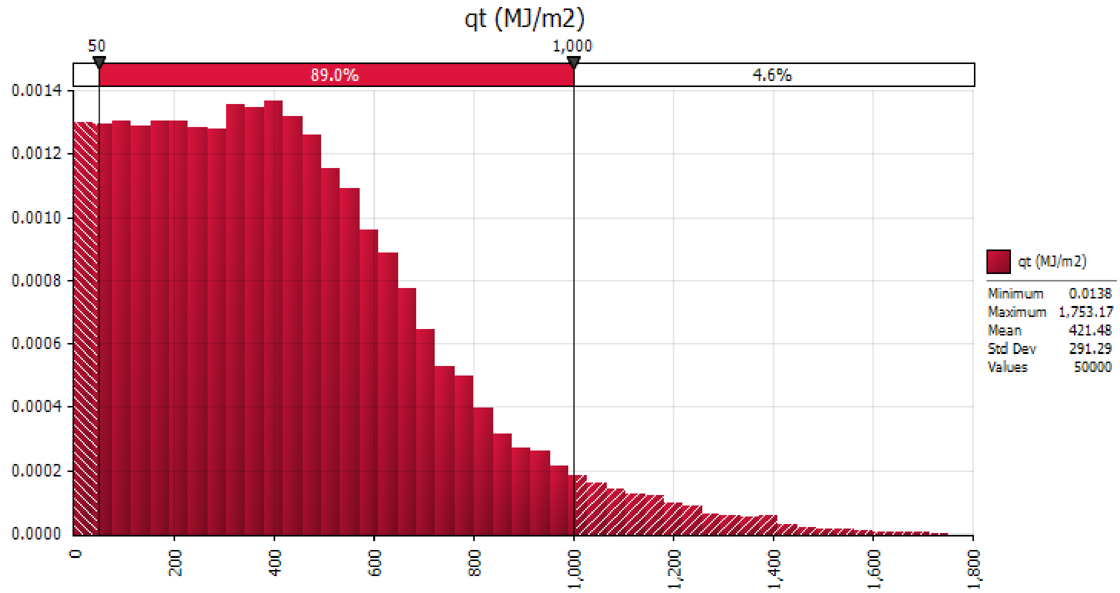


Figure 17. Case B probability density function for fire load per unit surface area showing limits of valid range.

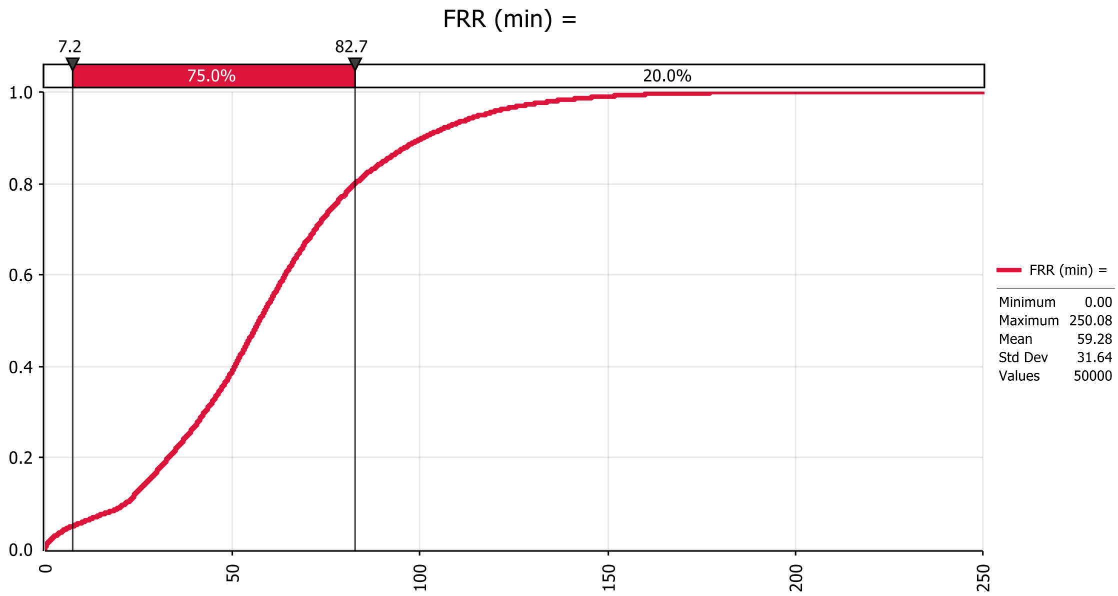


Figure 18. Case B ascending cumulative frequency distribution for FRR based on graphical t-e (unfiltered).

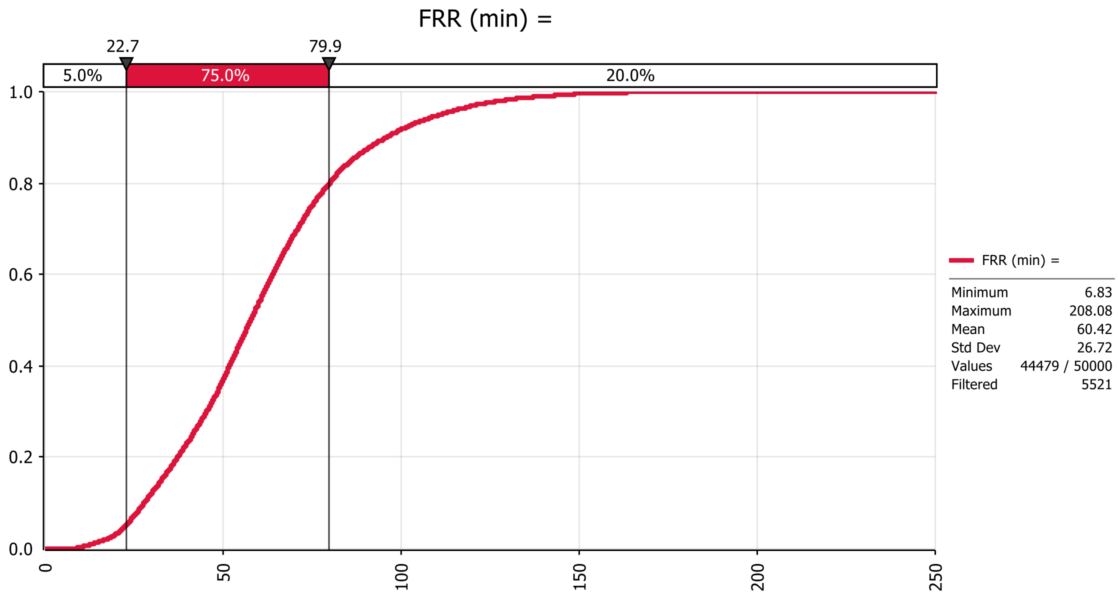


Figure 19. Case B ascending cumulative frequency distribution for FRR based on graphical t-e (filtered).

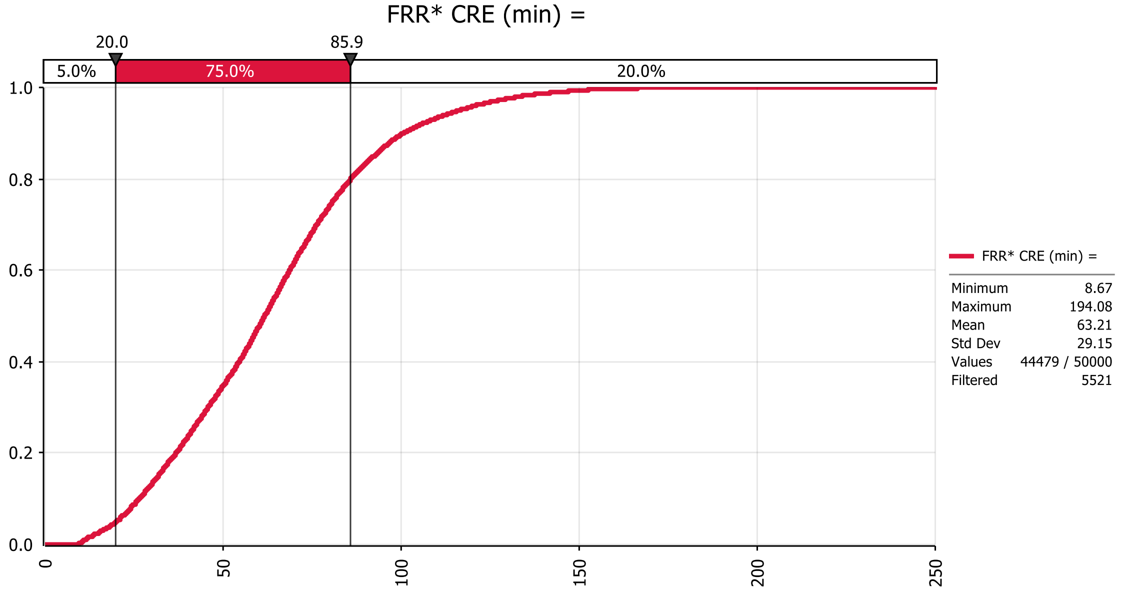


Figure 20. Case B ascending cumulative density function for FRR based on CRE method (filtered).

Figure 21 is a tornado plot demonstrating the sampled input parameter having the greatest effect on the output mean value of FRR based on graphical t-e. The fire load energy density has the greatest effect followed by the area of the wall openings as a percentage of the floor area, the load ratio and the area of the roof openings as a percentage of the floor area. Figure 22 and Figure 23 compare the design fire load energy density per unit floor area (input) with the actual fire load energy density per unit floor area after the results were filtered to remove the out-of-range iterations. This resulted in a 52 MJ/m^2 reduction in the 80th percentile value for the FLED.

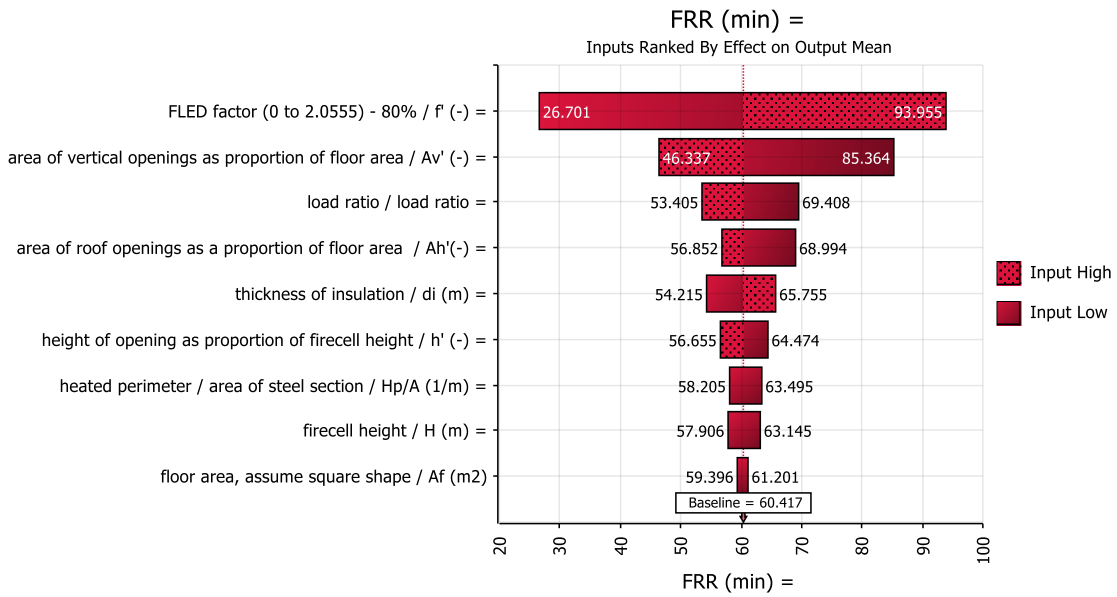


Figure 21. Case B tornado chart (change in output mean) for FRR based on graphical t-e (filtered).

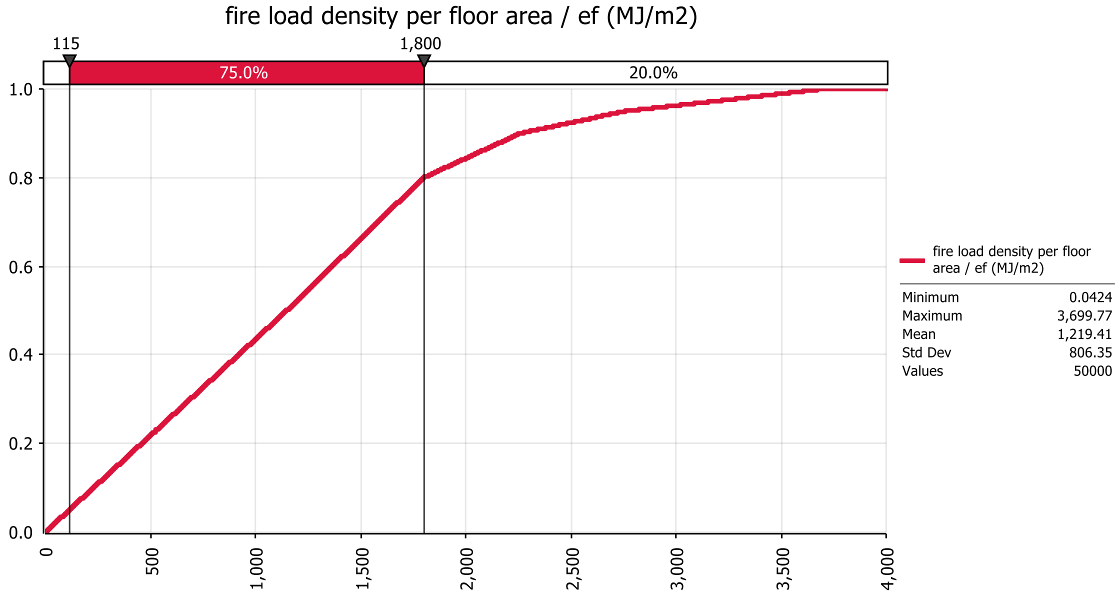


Figure 22. Case B ascending cumulative frequency distribution for the fire load energy density per unit floor area (unfiltered).

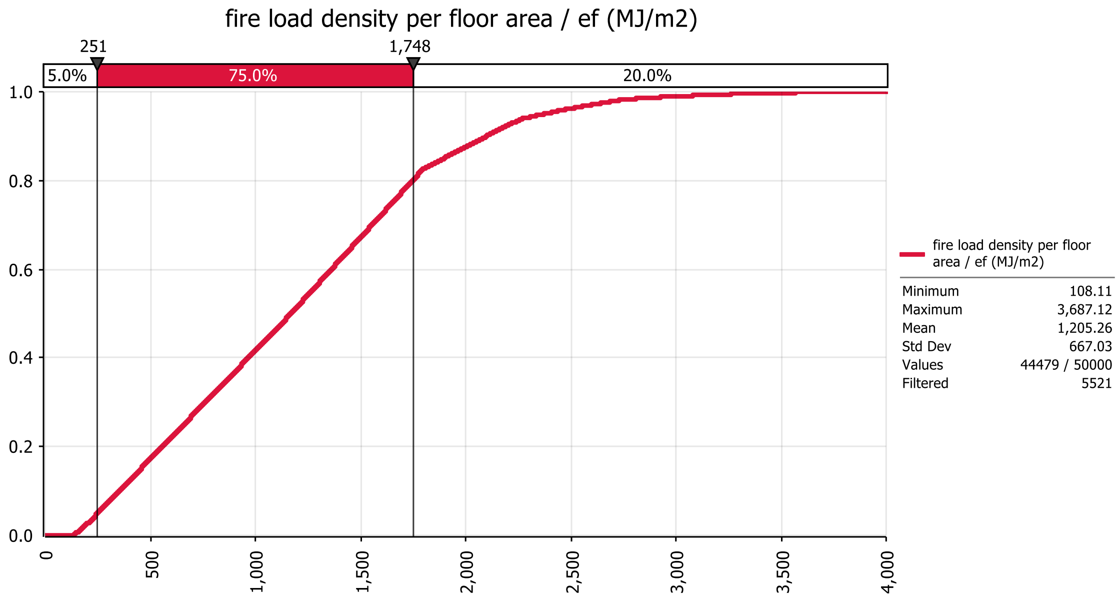


Figure 23. Case B ascending cumulative density function for the fire load energy density per unit floor area (filtered).

6.3 Case C – storage above 3 m

Case C considers a firecell height in the range 4–8 m (uniformly distributed). The storage height is set 1 m lower than sampled firecell height.

The upper 80th percentile value for the calculated fire severity based on the graphical time-equivalent method was 131 min as shown in Figure 24. If the results are filtered to exclude the out-of-range simulations, the upper 80th percentile value for the calculated fire falls to 92 min as shown in Figure 25. A high proportion of the simulations (18934/50000 = 38%) resulted in the fire load being outside the stated limits of applicability of the parametric equations with 34.6% being above the upper limit of 1000 MJ/m^2-surface area as shown in Figure 26. This limits the general applicability of the results for this case. However, since the upper 80th percentile values determined for the fire severity were significantly higher for the unfiltered set of results, it was decided to use the unfiltered data for this scenario for comparison with the other cases but with a cautionary note.

The upper 80th percentile value for the calculated fire severity based on the CRE method was 144 min as shown in Figure 27. Using the CRE method in the analysis resulted in a higher and more conservative calculation of the fire severity compared to the graphical time-equivalent method.

Roof venting was predicted to occur in 85% (42337/50000) of the simulations, and for these, the median time of roof failure was 21.4 min with a mode of 11.2 min.

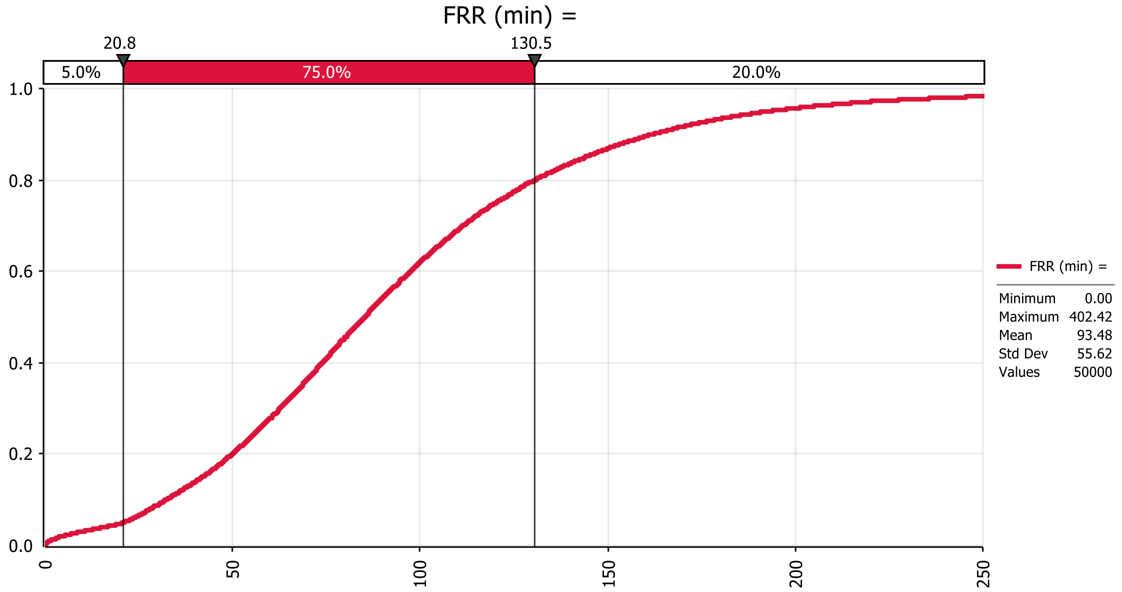


Figure 24. Case C ascending cumulative frequency distribution for FRR based on graphical t-e (unfiltered).

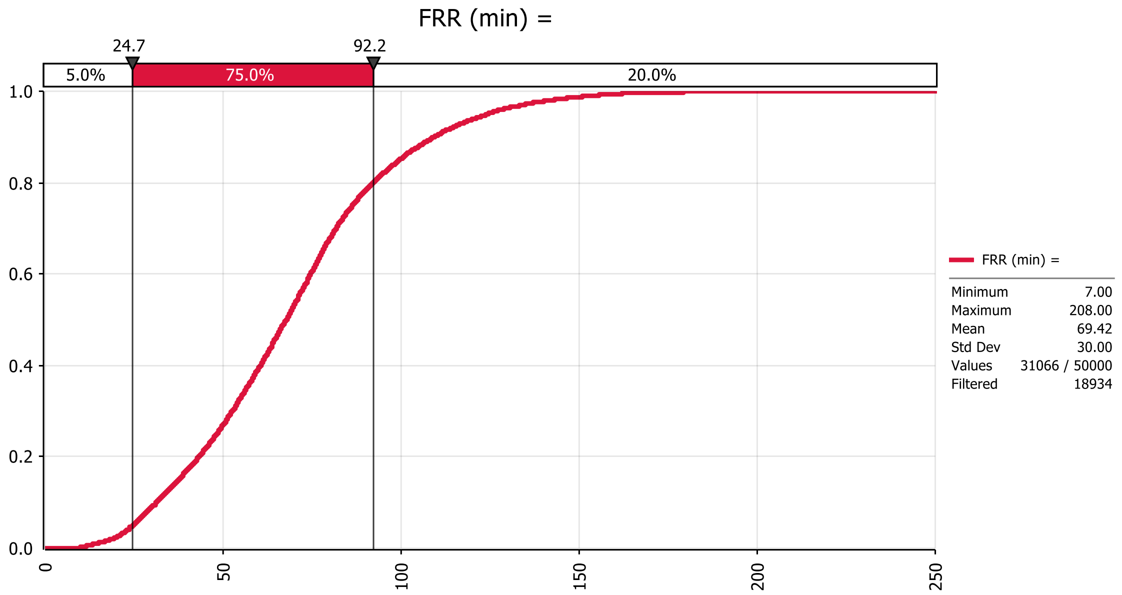


Figure 25. Case C ascending cumulative density function for FRR based on graphical t-e (filtered).

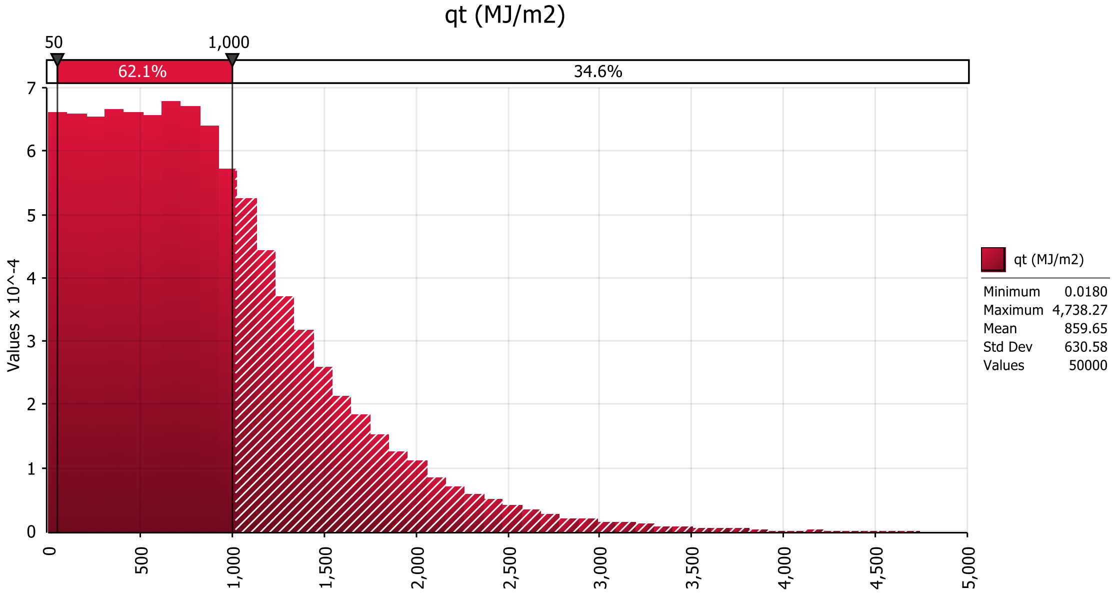


Figure 26. Case C probability density function for fire load per unit surface area showing limits of valid range.

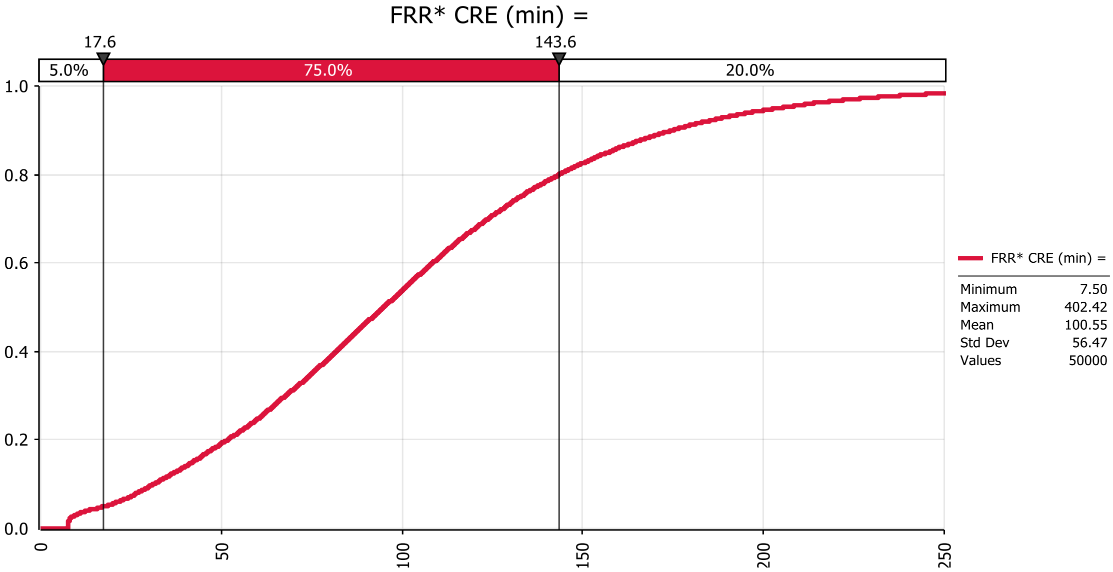


Figure 27. Case C ascending cumulative frequency distribution for FRR based on CRE method (unfiltered).

Figure 28 is a tornado plot demonstrating the sampled input parameter having the greatest effect on the output mean value of FRR based on graphical t-e. The fire load energy density has the greatest effect followed by the area of the wall openings as a percentage of the floor area, the firecell height, the floor area and the area of the roof openings as a percentage of the floor area. Figure 29 and Figure 30 compare the design fire load energy density per unit floor area (input) with the actual fire load energy density per unit floor area after the results were filtered to remove the out-of-range iterations. It can be seen there is a large reduction in the 80th percentile value after filtering, thus the filtered data does not reflect the intended design fire load density distribution initially specified.

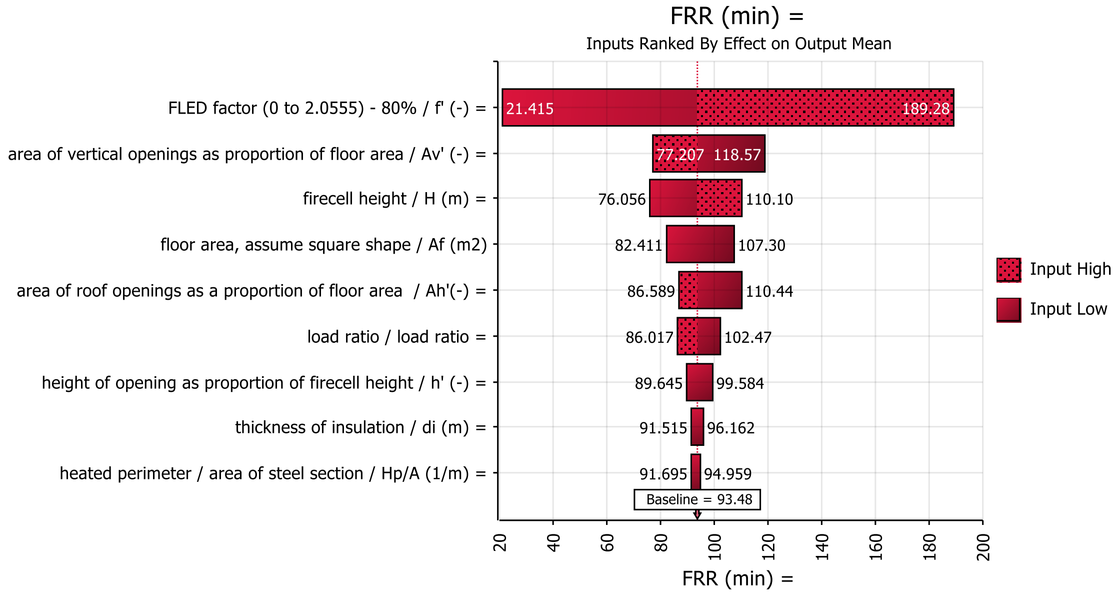


Figure 28. Case C tornado chart (change in output mean) for FRR based on graphical t-e (unfiltered).

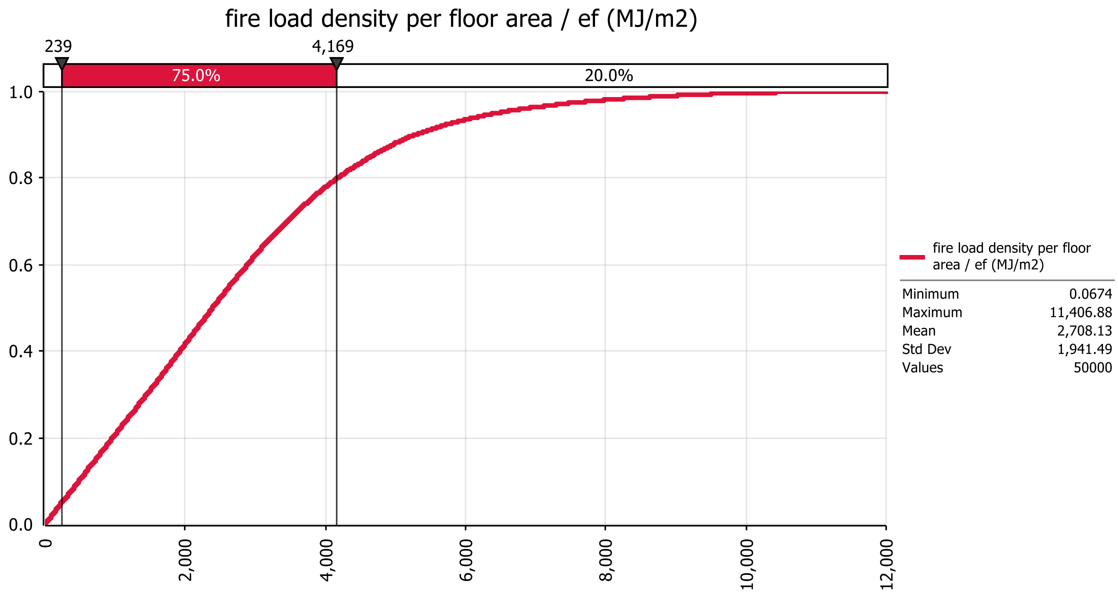


Figure 29. Case C ascending cumulative density function for the fire load energy density per unit floor area (unfiltered).

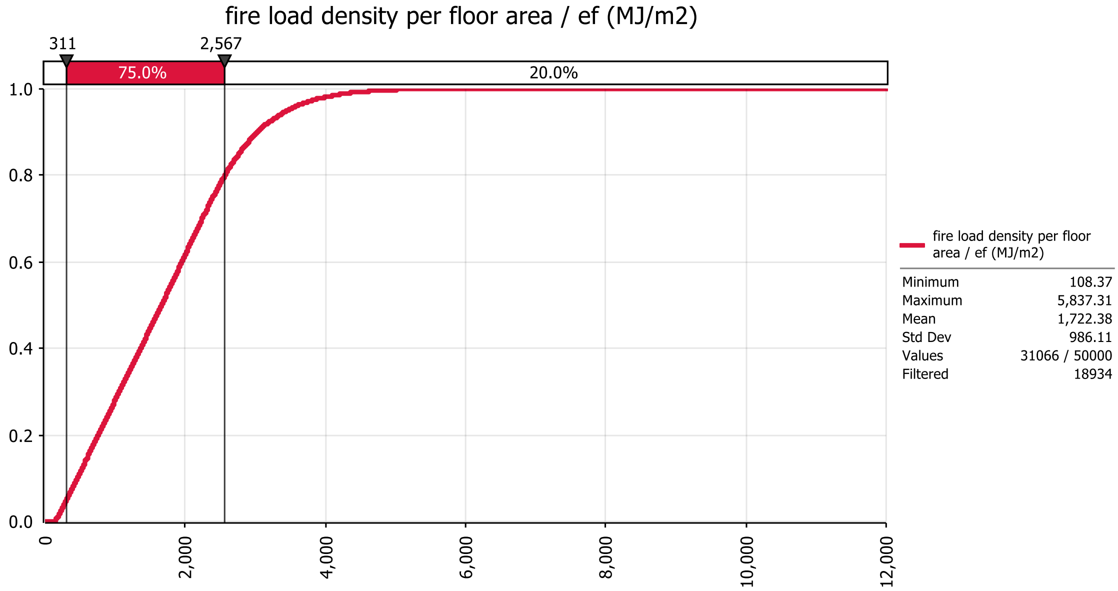


Figure 30. Case C ascending cumulative frequency distribution for the fire load energy density per unit floor area (filtered).

6.4 Case D – VM2 800 MJ/m^2

Case D was based on a firecell height in the range 2.7–6 m.

A cumulative frequency distribution is used for the fire load energy density, where the 80th percentile corresponds to 800 MJ/m^2, the 50th percentile is 524 MJ/m^2 (0.6555x800) and the 100th percentile is 1644 MJ/m^2 (2.0555x800).

The proportion of the simulations resulting in the fire load being outside the stated limits of applicability of the parametric equations was (7087 /50000 = 14.2%). However, these are all below the lower limit of the valid fire load range as shown in Figure 31.

The upper 80th percentile value for the calculated fire severity based on the graphical time-equivalent method was 56 min as shown in Figure 32. If the results are filtered to exclude the out-of-range simulations, the upper 80th percentile value for the calculated fire increases to 59 min as shown in Figure 33. The upper 80th percentile value for the calculated fire severity based on the CRE method was 59 min as shown in Figure 34. Using the CRE method in the analysis resulted in a very similar estimate of the fire severity compared to the graphical time-equivalent method.

Roof venting was predicted to occur in 45% (22346/50000) of the simulations, and for these, the median time of roof failure was 19.4 min with a mode of 15.5 min.

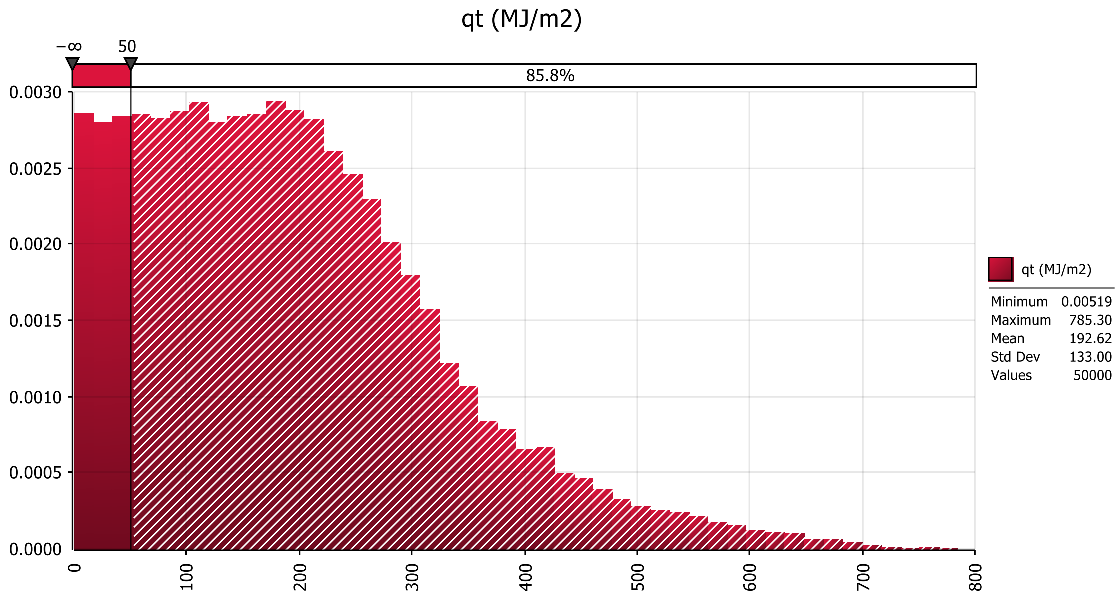


Figure 31. Case D probability density function for fire load per unit surface area showing limits of valid range.

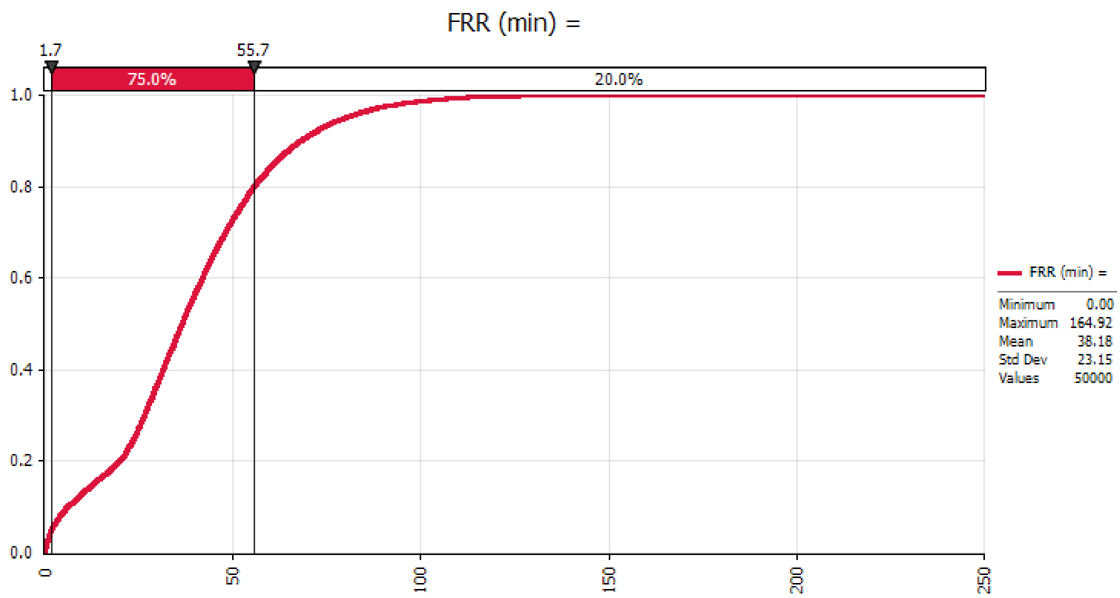


Figure 32. Case D ascending cumulative frequency distribution for FRR based on graphical t-e (unfiltered).

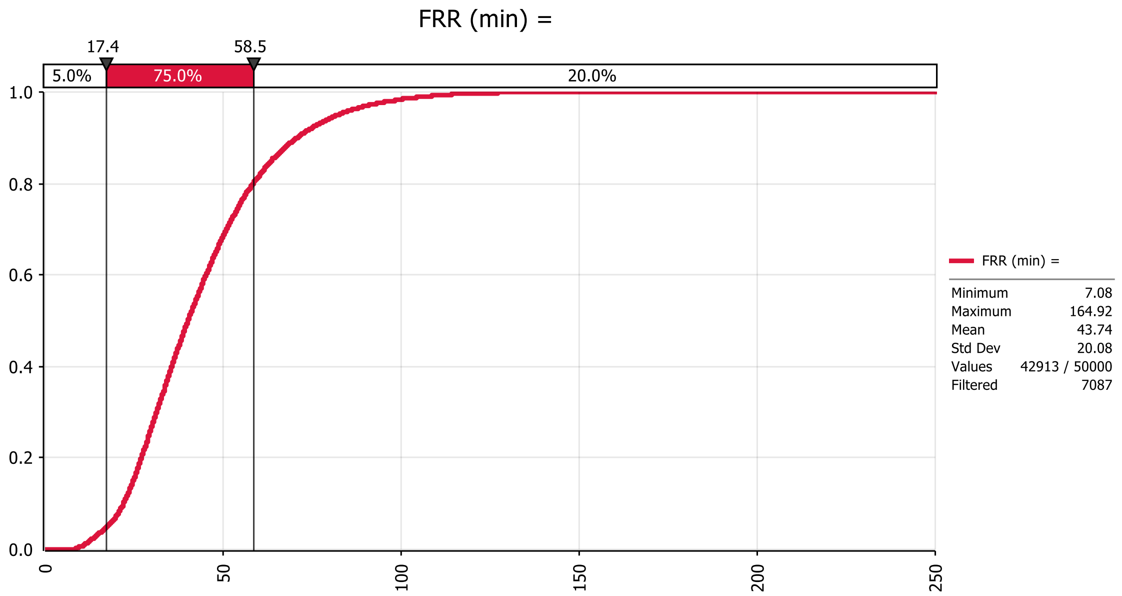


Figure 33. Case D ascending cumulative frequency distribution for FRR based on graphical t-e (filtered).

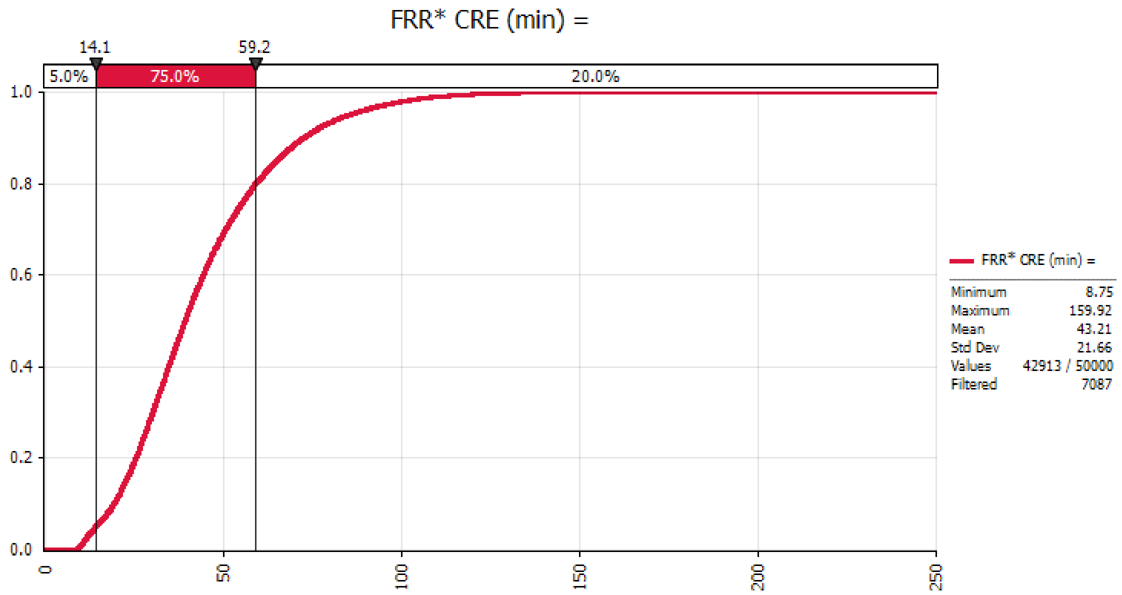


Figure 34. Case D ascending cumulative frequency distribution for FRR based on CRE method (filtered).

Figure 35 is a tornado plot demonstrating the sampled input parameter having the greatest effect on the output mean value of FRR based on graphical t-e. The fire load energy density has the greatest effect followed by the area of the wall openings as a percentage of the floor area, load ratio and steel protection thickness. Figure 36 and Figure 37 compare the design fire load energy density per unit floor area (input) with the actual fire load energy density per unit floor area after the results were filtered to remove the out-of-range iterations.

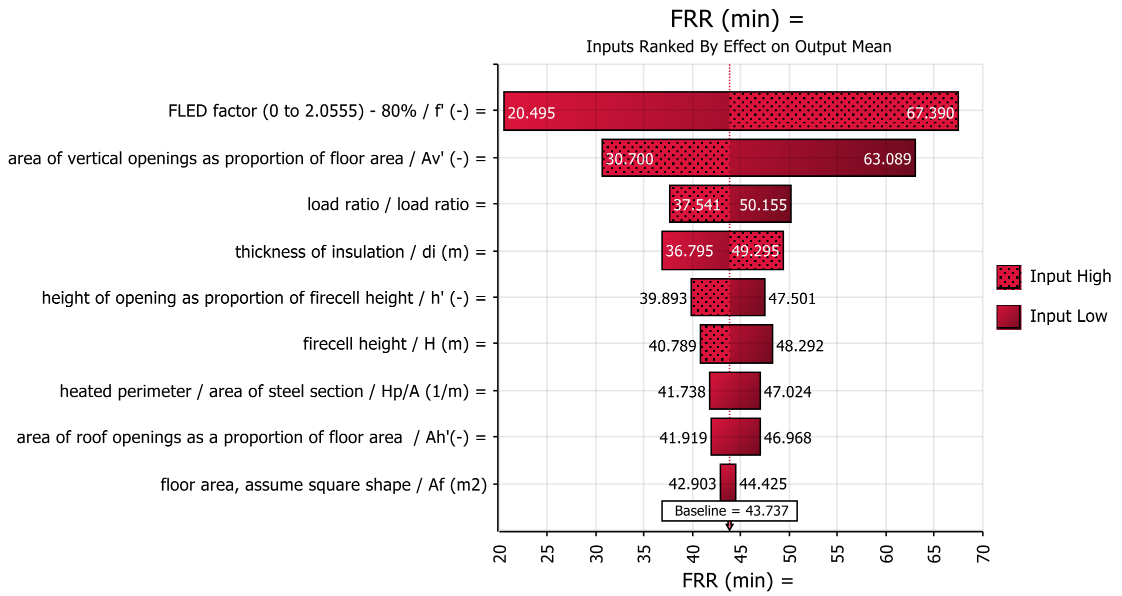


Figure 35. Case D tornado chart (change in output mean) for FRR based on graphical t-e (filtered).

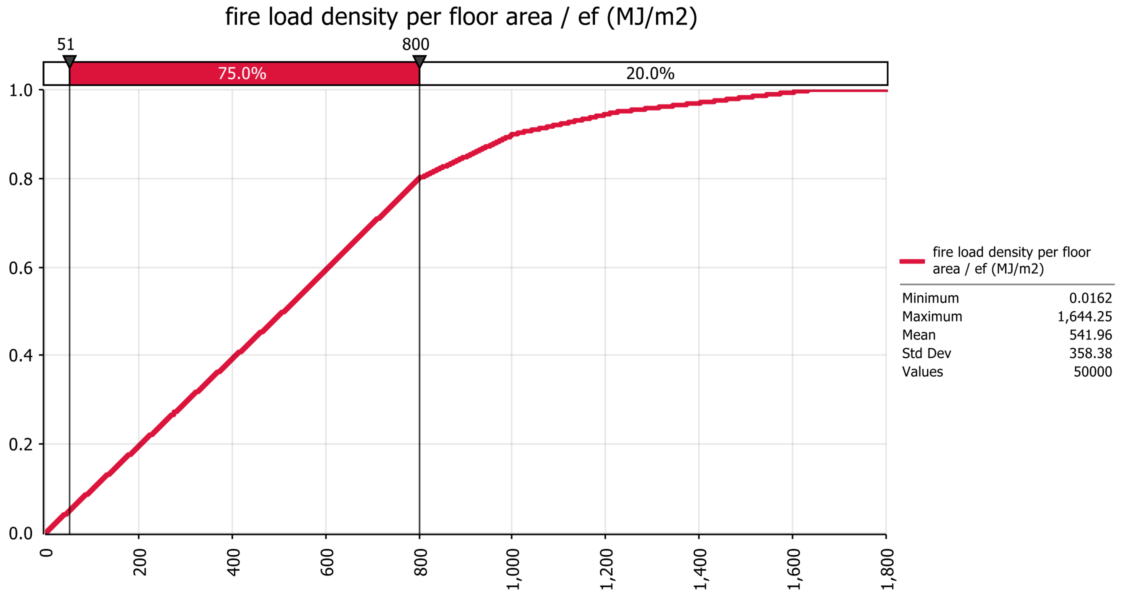


Figure 36. Case D ascending cumulative frequency distribution for the fire load energy density per unit floor area (unfiltered).

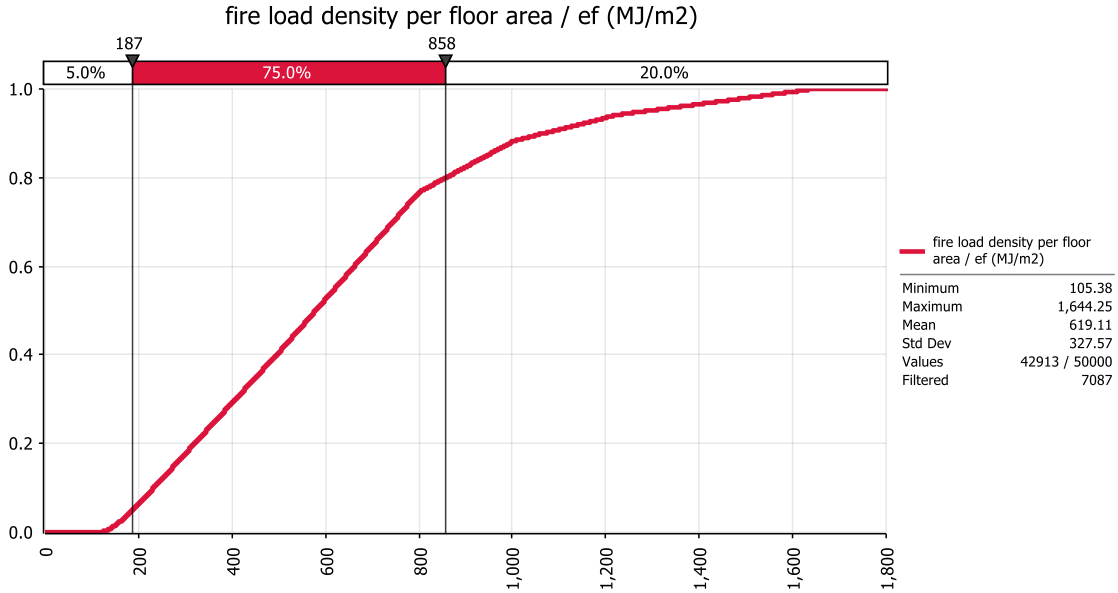


Figure 37. Case D ascending cumulative frequency distribution for the fire load energy density per unit floor area (filtered).

6.5 Case E – VM2 1200 MJ/m^2

Case E represents a firecell height in the range 2.7–6 m.

A cumulative frequency distribution is used for the fire load energy density, where the 80th percentile corresponds to 1200 MJ/m^2, the 50th percentile is 787 MJ/m^2 (0.6555x1200) and the 100th percentile is 2467 MJ/m^2 (2.0555x1200).

The proportion of the simulations resulting in the fire load being outside the stated limits of applicability of the parametric equations was 9.7% (4835/50000) with most of these falling below the lower limit of the valid range as shown in Figure 38.

The upper 80th percentile value for the calculated fire severity based on the graphical time-equivalent method was 68 min as shown in Figure 39. If the results are filtered to exclude the out-of-range simulations, the upper 80 percentile value for the calculated fire increases to 70 min as shown in Figure 40. The upper 80th percentile value for the calculated fire severity based on the CRE method was 74 min as shown in Figure 41. Using the CRE method in the analysis resulted in a higher and more conservative calculation of the fire severity.

Roof venting was predicted to occur in 59.6% (29813/50000) of the simulations, and for these, the median time of roof failure was 20.5 min with a mode of 18.8 min.

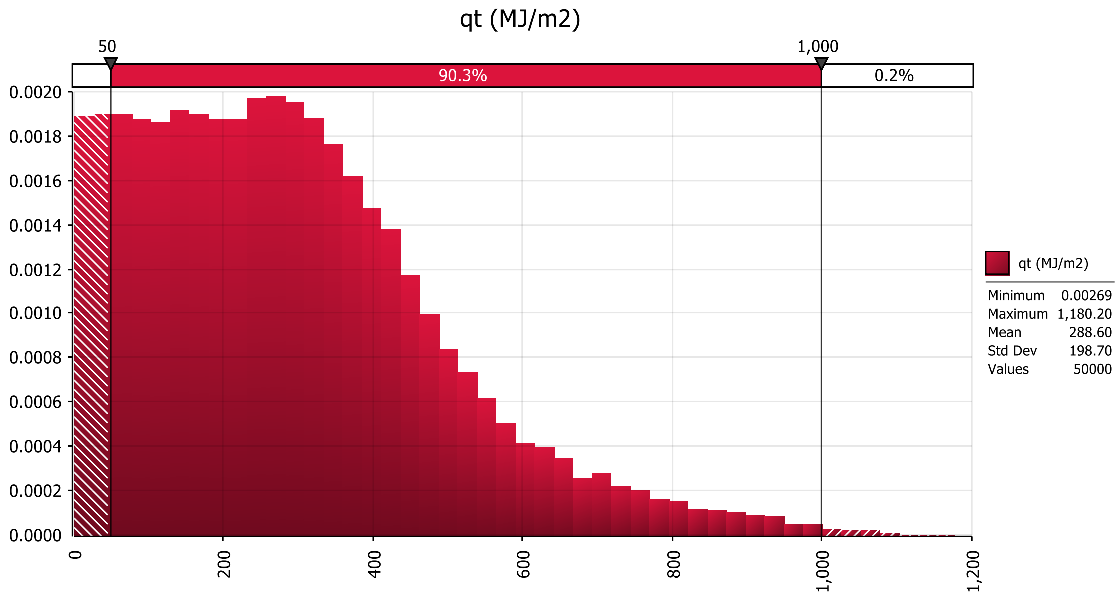


Figure 38. Case E probability density function for fire load per unit surface area showing limits of valid range.

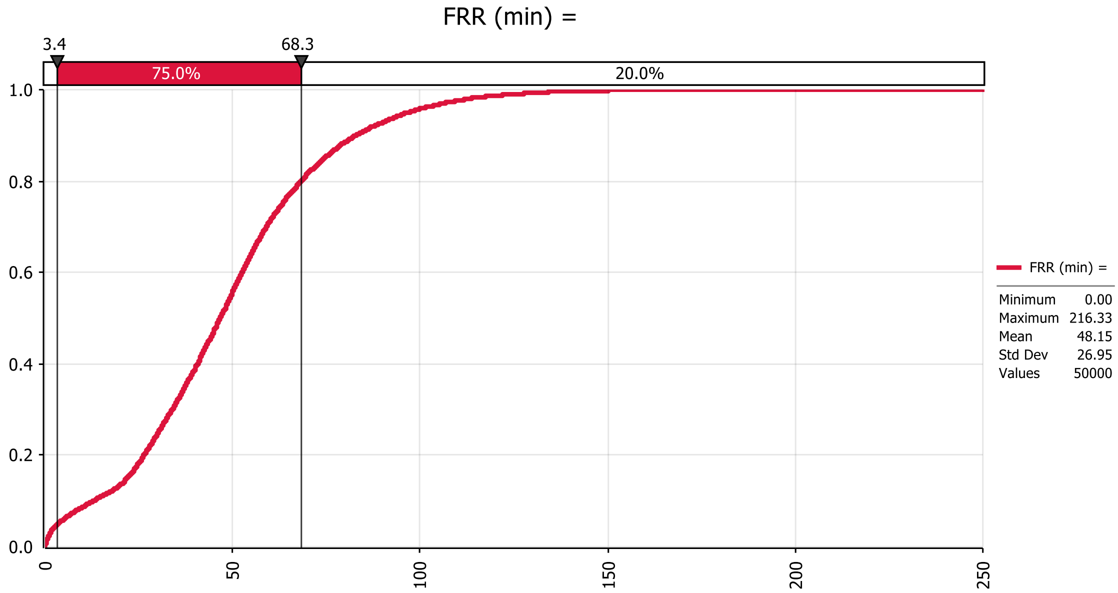


Figure 39. Case E ascending cumulative frequency distribution for FRR based on graphical t-e (unfiltered).

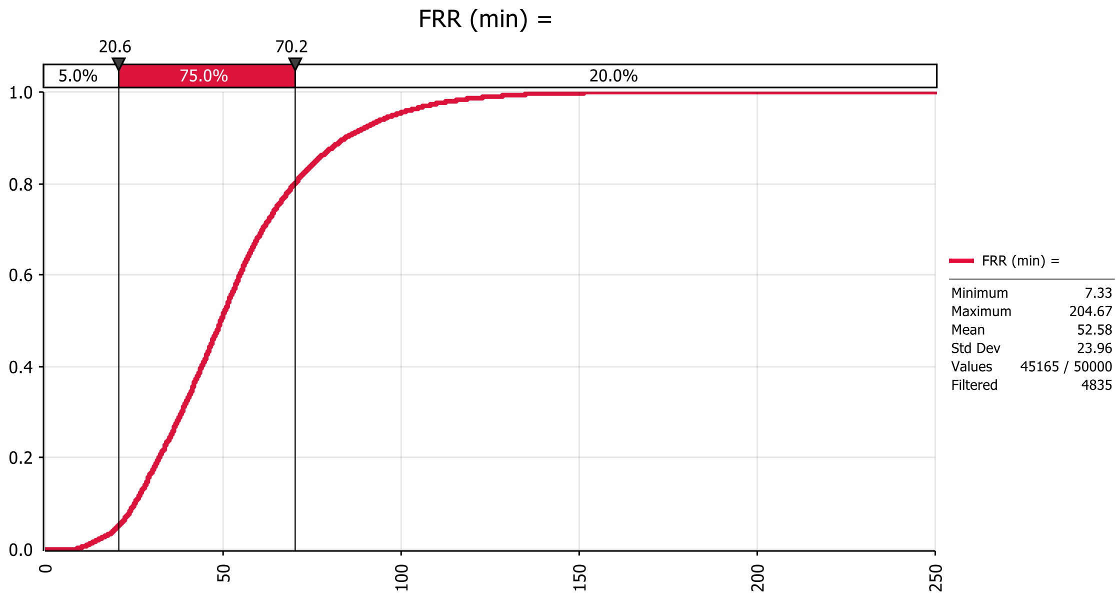


Figure 40. Case E ascending cumulative density function for FRR based on graphical t-e (filtered).

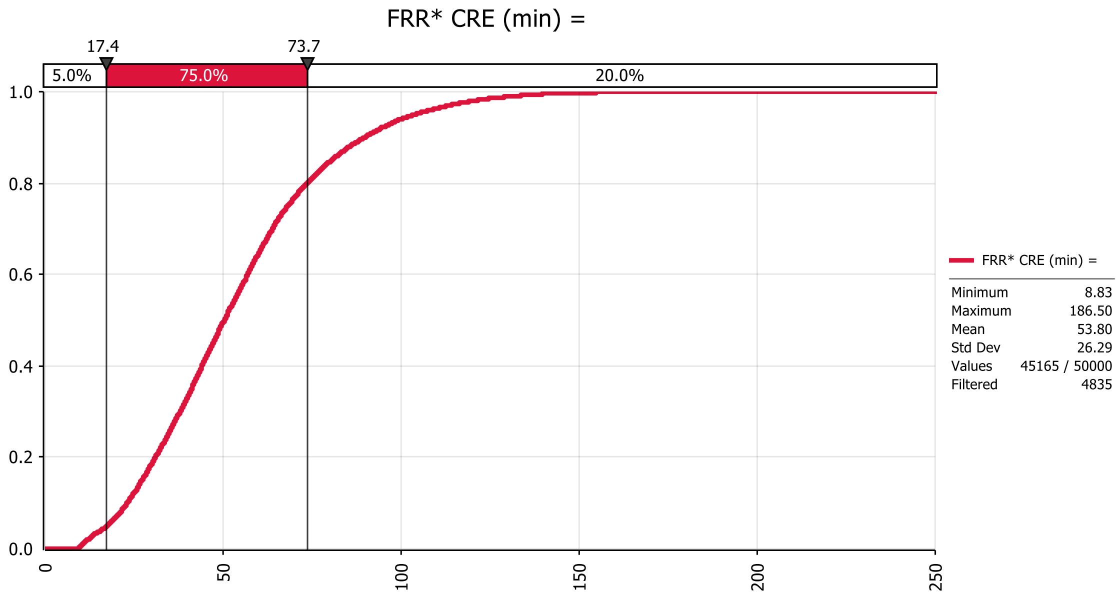


Figure 41. Case E ascending cumulative frequency distribution for FRR based on CRE method (filtered).

Figure 42 is a tornado plot demonstrating the sampled input parameter having the greatest effect on the output mean value of FRR based on graphical t-e. The fire load energy density has the greatest effect followed by the area of the wall openings as a percentage of the floor area, load ratio and protection thickness. Figure 43 and Figure 44 compare the design fire load energy density per unit floor area (input) with the actual fire load energy density per unit floor area after the results were filtered to remove the out-of-range iterations. This resulted in an increase of 53 MJ/m^2 in the 80th percentile of the FLED.

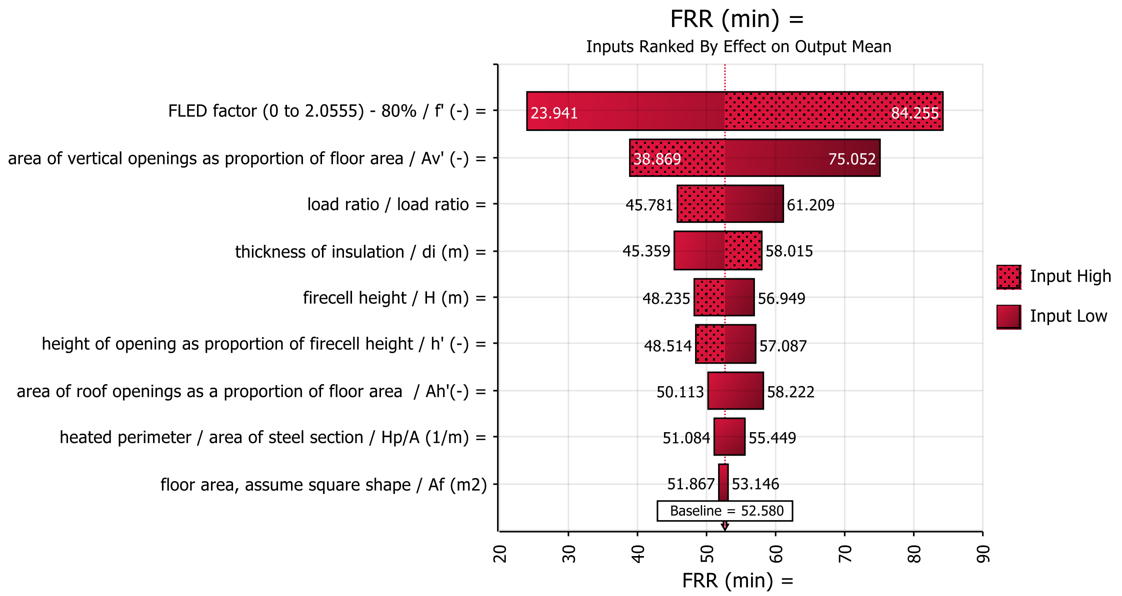


Figure 42. Case E tornado chart (change in output mean) for FRR based on graphical t-e (filtered).

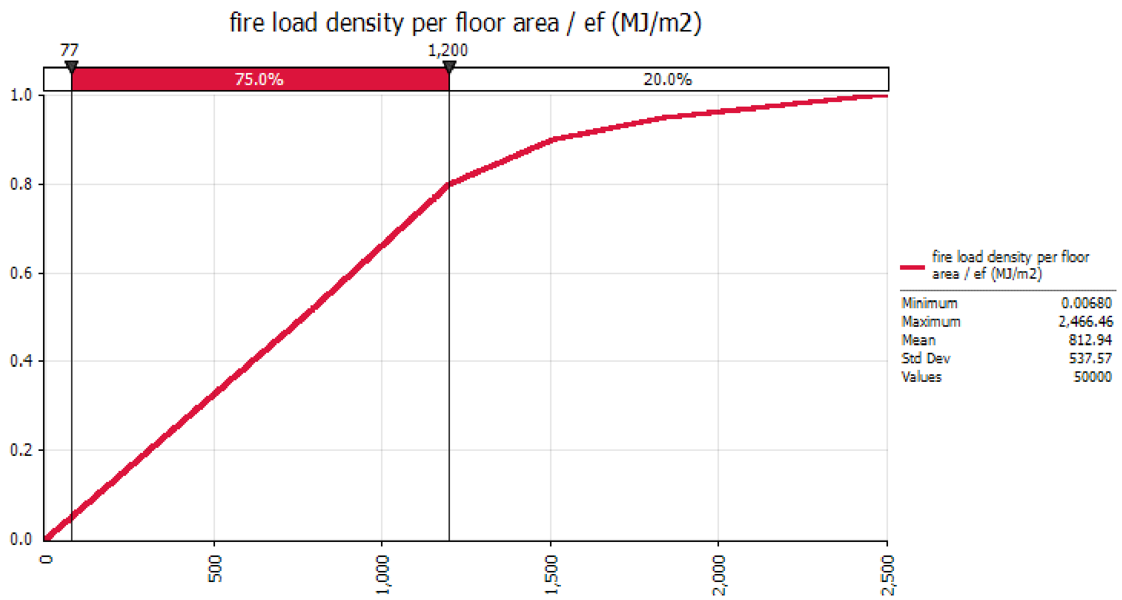


Figure 43. Case E ascending cumulative frequency distribution for the fire load energy density per unit floor area (unfiltered).

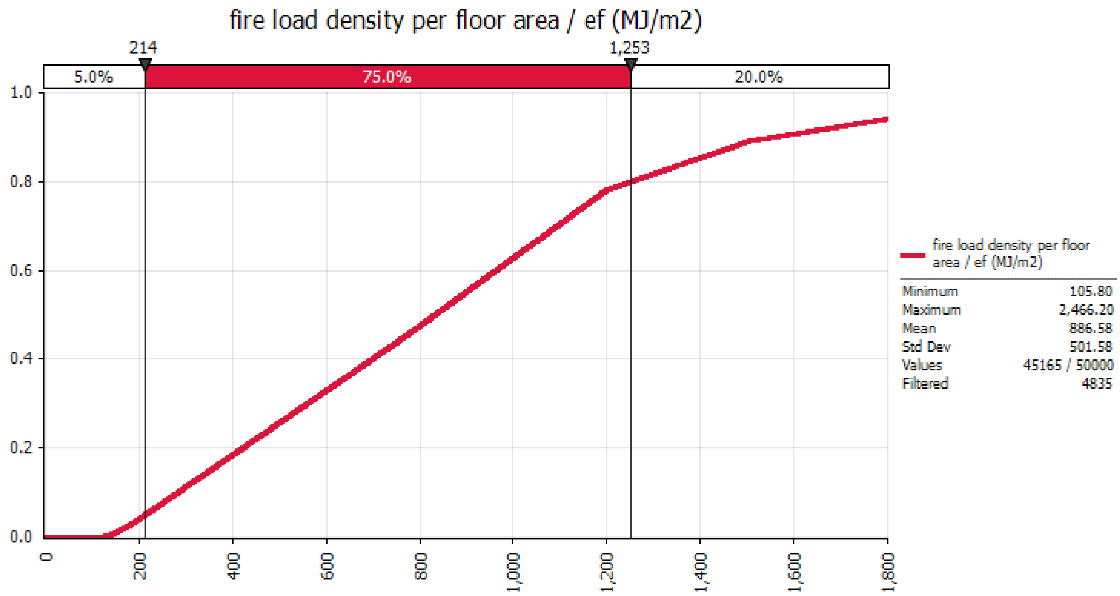


Figure 44. Case E ascending cumulative frequency distribution for the fire load energy density per unit floor area (filtered).

6.6 Summary of results

The results for the predicted FRR based on the graphical t-e method for the percentiles are tabulated in Table 12, and the results using the CRE method are tabulated in Table 13. The tables show filtered results, except for Case 3 (storage above 3 m) where the unfiltered results are shown. The ascending cumulative frequency distribution for the fire severity based on the graphical t-e method is shown in Figure 45 while the cumulative frequency distribution for fire severity based on the CRE method is shown in Figure 46.

Table 12. FRR values (in minutes) versus percentiles based on the graphical t-e method for Cases A to E.

Percentile	Case A	Case B	Case C*	Case D	Case E
10%	19	28	32	22	25
15%	21	33	42	25	29
20%	23	37	50	27	32
25%	25	42	57	29	35
30%	26	45	63	31	38
35%	28	49	68	34	41
40%	30	52	74	36	44
45%	32	55	79	38	47
50%	33	58	85	40	49
55%	35	61	91	43	52
60%	38	64	97	45	55
65%	40	67	104	48	58
70%	43	71	112	51	61
75%	46	75	120	54	65
80%	49	80	131	59	70
85%	53	86	144	64	76
90%	59	96	162	71	85
95%	68	111	193	82	98
99%	87	139	281	106	125

* based on unfiltered data

Table 13. FRR values (in minutes) versus percentiles based on the CRE method for Cases A to E.

Percentile	Case A	Case B	Case C*	Case D	Case E
10%	15	26	31	19	23
15%	18	32	42	23	27
20%	20	37	52	25	31
25%	22	41	61	28	35
30%	24	46	68	30	38
35%	26	50	75	32	41
40%	27	55	82	35	44
45%	29	58	88	37	47
50%	31	62	95	39	50
55%	33	65	102	42	54
60%	35	69	109	44	57
65%	37	72	116	47	60
70%	40	76	124	51	64
75%	43	81	133	55	68
80%	47	86	144	59	74
85%	51	92	157	65	80
90%	57	101	175	73	90
95%	68	116	204	85	104
99%	89	144	267	110	130

* based on unfiltered data

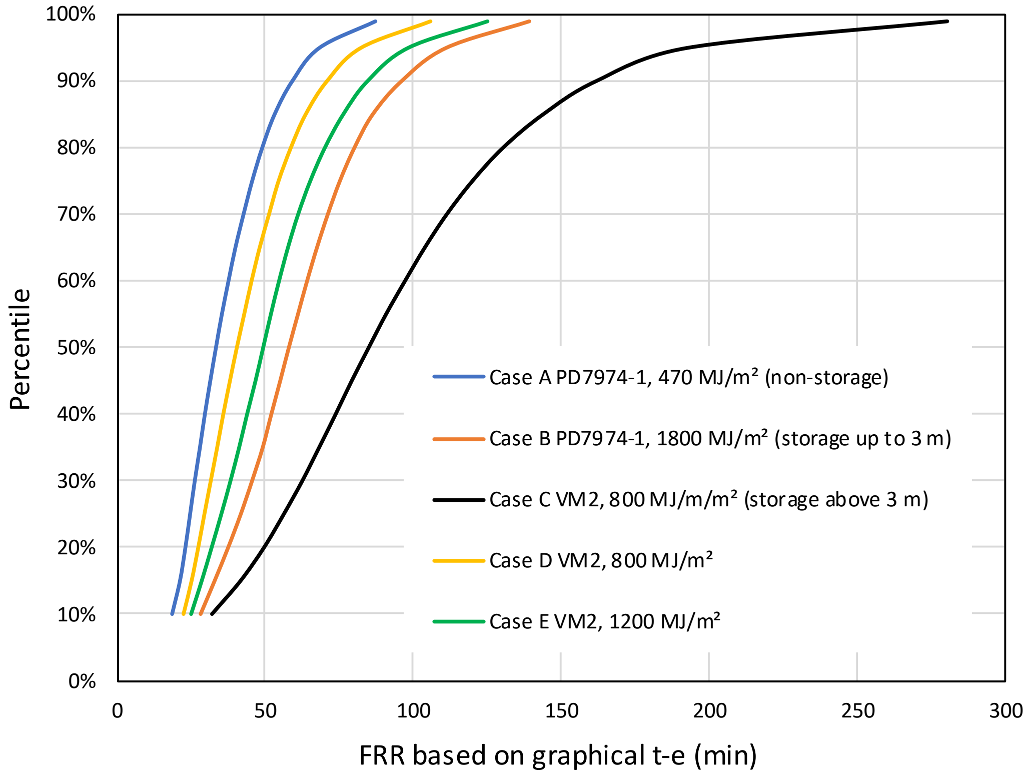


Figure 45. Ascending cumulative frequency distribution for FRR based on graphical t-e.

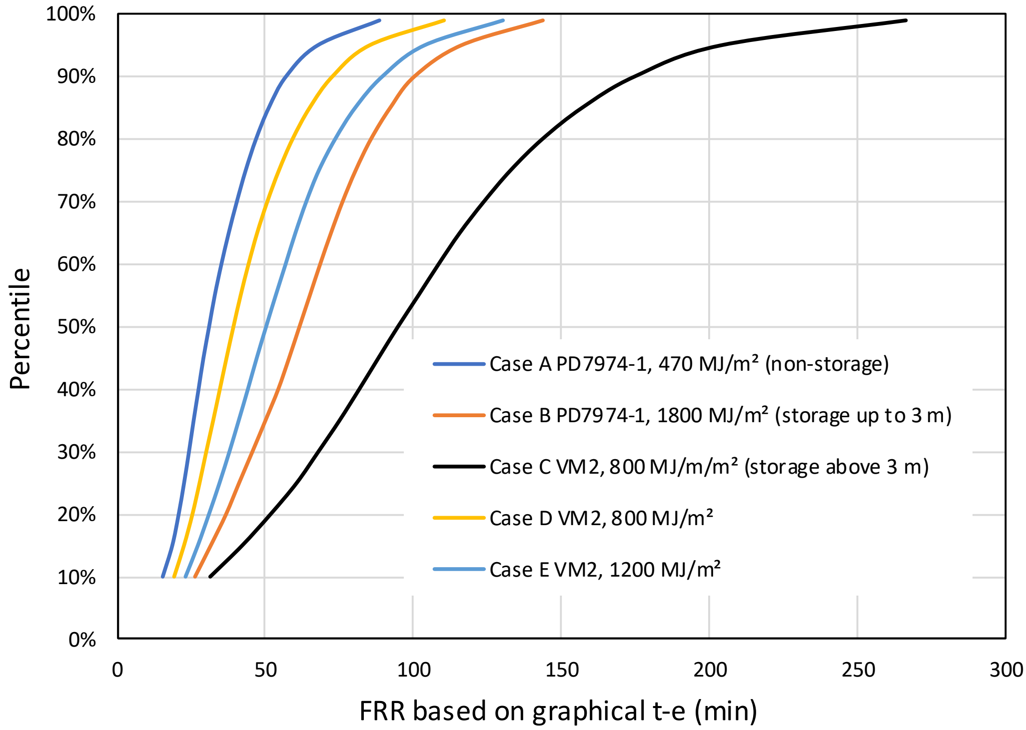


Figure 46. Ascending cumulative density function for FRR based on CRE method.

7. Discussion

7.1 FRR based on graphical t-e versus CRE

Deriving the fire resistance rating percentile values using the CRE method generally provided slightly less conservative or shorter FRR times for less severe fires compared to using the graphical t-e method. Conversely, the CRE method gave more conservative or longer FRR times for more severe fires as illustrated in Figure 47. While the CRE method appears to be a simpler but still reasonable approach for quantifying the fire severity, this report mainly presents the FRR based on the graphical t-e as it is a more generally accepted methodology internationally.

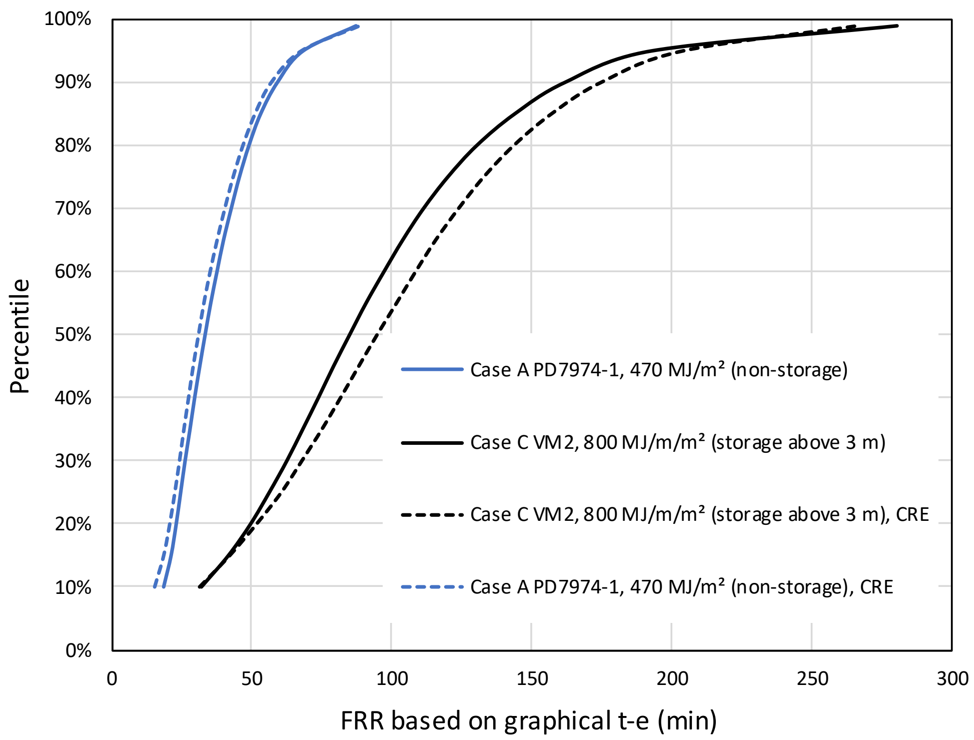


Figure 47. Comparing cumulative frequency distribution for FRR based on t-e and FRR based on CRE method.

7.2 Construction materials

Construction materials used for the bounding surfaces of the compartment influence heat loss and the gas temperatures within the compartment. This is represented by the thermal inertia parameter *b* in Eqn. 4-4. The cumulative frequency curves for the FRR based on graphical t-e for Cases A and C and comparing steel (b=2200) and plasterboard (b=720) construction is shown in Figure 48.

For the lower fire load and shorter duration fire represented by Case A, the fire severity and fire resistance times are always longer in the case of plasterboard compared to steel construction. However, this is not always the case for Case C (with more fire load) where the curves cross over to become less severe for the steel construction compared to plasterboard at longer durations. Earlier in the fire for the plasterboard construction, the fire appears to be less severe. The reason for this could be due to earlier failure of the unprotected steel element due to the higher temperatures initially and earlier roof venting for the more insulating plasterboard enclosure compared to steel.

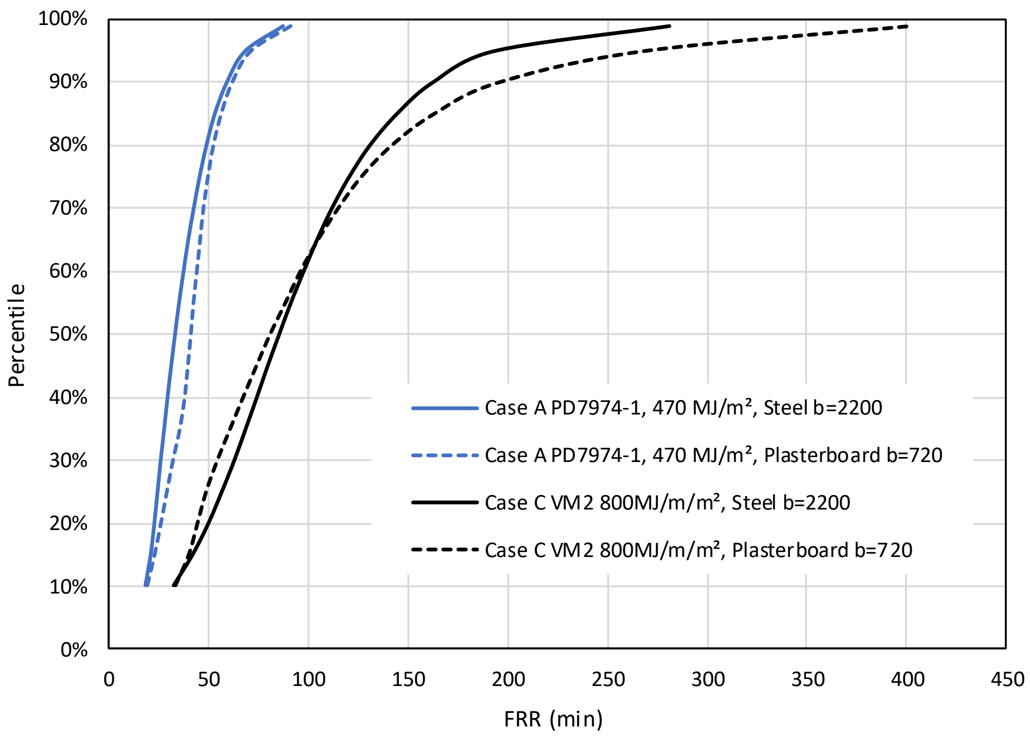


Figure 48. Comparison of cumulative frequency distribution curves for FRR based on graphical t-e for steel and plasterboard-lined compartments.

7.3 Effect of including roof ventilation

The impact of allowing for the potential fire venting through the roof structure in addition to vertical openings in the external wall can be seen by comparing the cumulative frequency curves for the FRR based on graphical t-e for Cases A and C as shown in Figure 49. As expected, allowing for roof ventilation in the analysis leads to a reduction in fire severity giving a lower FRR value for a given percentile.

It is also noted that the analysis has constrained the ventilation factor to be within the stated valid range for the parametric equations. Therefore, in practice, there could be a much larger available ventilation area than assumed in the analysis, especially in the event of the roof collapsing. This is likely to result in added conservatism in the results presented.

In the cases where fire venting was predicted, the median time of venting due to failure of the roof support structure was consistently in the range 19–21 minutes. Engineered smoke/heat venting systems were not considered in the analysis, but if present, they would be expected to result in earlier venting.

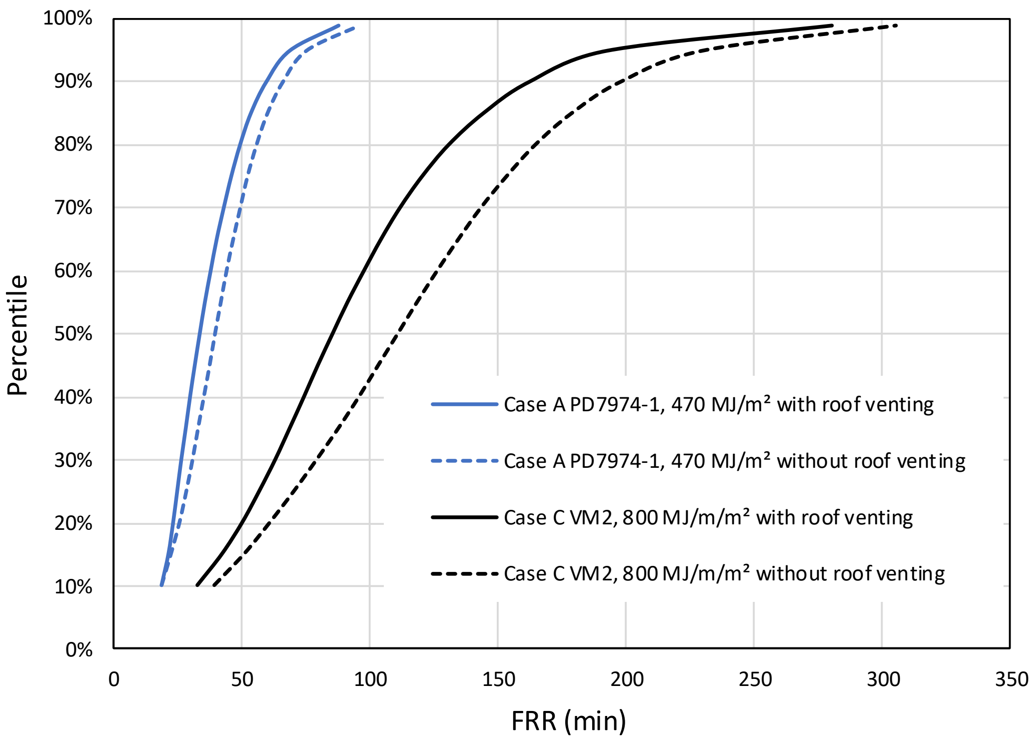


Figure 49. Comparison of cumulative frequency distribution curves for FRR based on graphical t-e with wall ventilation only and with both wall and roof ventilation.

7.4 Limitation of results based on fire load quantity

The parametric time temperature curves are inherently correlations with stated ranges of validity as described in section 4.1.1. In particular, the fire load density ($q_{t,d}$) related to the total surface area of the enclosure is required to be in the range 50–1000 MJm^{-2}.

$q_{t,d}$ = the design value of the fire load density related to the total surface area of the enclosure A_t whereby $q_{t,d} = q_{f,d} \times A_f / A_t$ with $50 \leq q_{t,d} \leq 1000$ MJm^{-2}.

$q_{f,d}$ = the design value of the fire load density related to the surface area of the floor in MJm^{-2}.

The minimum fire load density has minimal effects on the output, but the maximum becomes restrictive for larger fire compartments as shown in Figure 50. In our analysis, a distribution for the fire load density per unit floor area has been sampled, with the results filtered to exclude those iterations that included sampled values of fire load falling outside the stated range. This results in a discrepancy between the intended design fire load density used as input to the calculations and the actual fire load distribution represented by the filtered set of results.

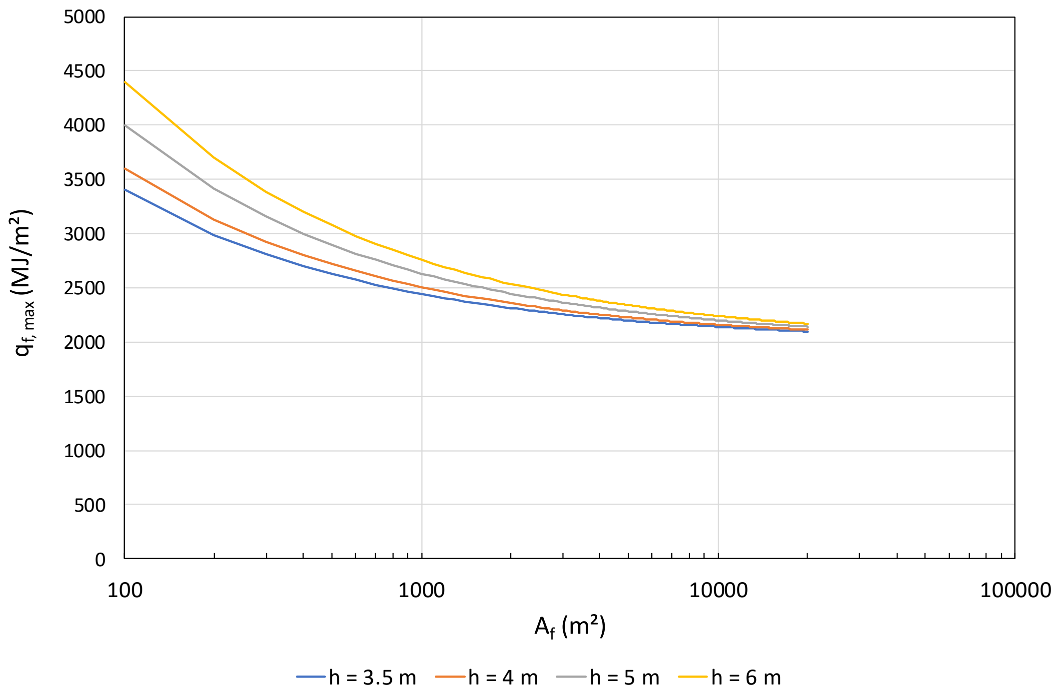


Figure 50. Maximum fire load density (per unit floor area) for a range of fire compartment sizes and roof heights.

7.5 Effect of fire sprinkler installation

As part of the Natural Fire Safety Concept study (Schleich, 2005, Chapter 3), calibration of reliability values was undertaken to determine the differentiation factor for sprinklers. As described in section 3.2, a value of 0.61 (as used in EN 1991-1-2:2002 for an automatic water extinguishing system with no independent supply) is based on a probability of sprinklers failing to extinguish the fire of 0.02, a probability of there being a fully engulfed compartment fire over the life of the building (55 years) of 2.2 x 10^{-2} assuming a floor area of 1000 m^2. The target failure probability for the structure was taken as 7.23 x 10^{-5} over the life of the building corresponding to a structural reliability index of 3.8.

Using these assumptions, the probability of there being a fully engulfed compartment fire over the life of the building if the building were sprinklered is:

$$P_{fi,55} = 2.2 \times 10^{-2} \times 0.02 = 4.4 \times 10^{-4} \qquad \textit{Eqn. 7-1}$$

The reliability index β_{fi} for this sprinklered case can be calculated assuming a Gaussian normal distribution where Φ^{-1} is the inverse of the standard normal cumulative distribution.

$$\beta_{fi} = \Phi^{-1}\,(7.23 \times 10^{-5} / \, 4.4 \times 10^{-4}) = \Phi^{-1}\,(0.1643) = 0.977 \qquad \textit{Eqn. 7-2}$$

The global factor applying to the characteristic fire load (with sprinklers) is:

$$\gamma_{qf} = 0.863605\left(1 - 0.233909\left(0.577216 + \ln(-\ln(\Phi(0.9\beta_{fi})))\right)\right) = 0.0612 \qquad \textbf{Eqn. 7-3}$$

This assumes that the fire load is represented by a Gumbel Type I distribution with a variation coefficient of 0.3 with an 0.8 fractile for the characteristic fire load as given by Schleich (2005).

The differentiation factor for the sprinklered case (with no independent supply) is:

$$\delta = \frac{\gamma_{qf\ (\text{with sprinklers})}}{\gamma_{qf\ (\text{without sprinklers})}} = \frac{0.0612}{1.74} = 0.61 \qquad \textbf{Eqn. 7-4}$$

This factor is intended to be applied to the 80th percentile characteristic fire load. Similarly, for a sprinkler system with one independent water supply, the differentiation factor becomes 0.53 (based on a probability of sprinklers failing to extinguish the fire of 0.01), and for two independent water supplies it is 0.43 (based on a probability of sprinklers failing to extinguish the fire of 0.005) from Schleich (2005, Table 17).

Arguably, the sprinkler reliabilities assumed in EN 1991-1-2:2002 could be too high for New Zealand given that Gravestock (2008) recommended using a mean effectiveness of 90% (for offices) and Frank et al. (2013) estimated sprinkler system effectiveness based on New Zealand Fire Service data for the period 2001–2010 as only 86% (mean). Table 14 shows the fire load differentiation factors calculated for different assumed sprinkler reliability values for a floor area of 1000 m^2. It is interesting that only the dual independent supply case with 0.5% sprinkler failure rate is lower than 0.5, which is the value often assumed in New Zealand for reducing the fire resistance rating with a sprinkler system. However, the fire load differentiation factor reduces with floor area as illustrated in Figure 51 such that, if a floor area of 400 m^2 was used instead of 1000 m^2, the factor would reduce from 0.61 to 0.50.

Assuming that there is a linear relationship between fire load and fire severity, it is reasonable that these fire load differentiation factors could also be used to determine the trade-off given for the required fire resistance in sprinklered buildings.

Table 14. Fire load differentiation factor dependent on sprinkler reliability for a floor area of 1000 m^2.

Probability of sprinkler failure	No independent water supply	One independent water supply (the assumed probability of sprinkler failure is ½ that shown in column 1)	Two independent water supplies (the assumed probability of sprinkler failure is ¼ that shown in column 1)
2% (e.g. EN 1991-1-2:2002)	0.61	0.53	0.43
5%	0.71	0.63	0.56
10%	0.78	0.71	0.63

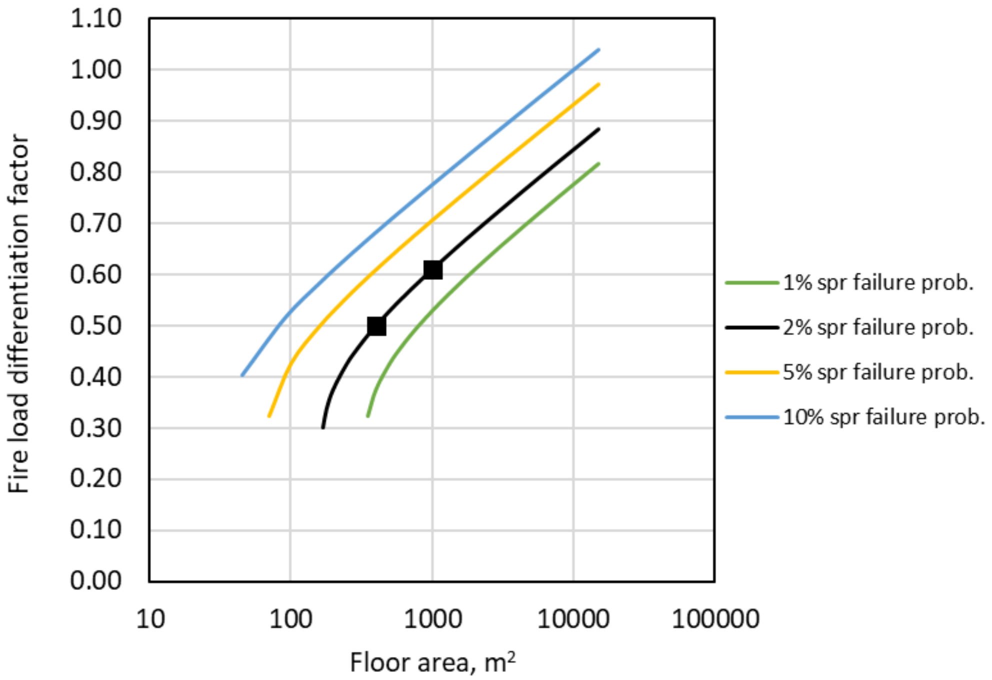


Figure 51. Fire load differentiation factors versus floor area for a sprinklered enclosure with sprinkler failure probabilities 1%, 2%, 5% and 10%.

7.6 C/AS5 change implications

The analysis here only considers external fire spread from single-storey industrial or warehouse buildings with non-fire rated lightweight steel roofs. It allows for potential failure of the roof, which will allow the fuel to burn out quicker and for a larger proportion of the heat to escape. Adding specific requirements for buildings of this design adds an additional level of complexity that was not intended under the simple philosophy for the current Acceptable Solutions. Any changes to the roof design that could prevent failure (such as adding a lining) in such a building will require the analysis to be modified accordingly as illustrated in Figure 49 for Cases A and C.

Reducing the fire resistance rating requirements for these specific buildings also potentially introduces a conflict with C/VM2 for the instances where C/VM2 will require greater fire resistance than the Acceptable Solutions will. This conflicts with the philosophy that Acceptable Solution designs are intended to be more conservative than C/VM2 buildings. Since the C/VM2 approach was not developed on a risk basis, it should also be revisited to realign with the Acceptable Solutions if they are changed.

Reducing the fire resistance rating requirements increases the dependence on the fire service to manage external fire spread across the boundary and may have knock-on effects on firefighting water and firefighting appliance access requirements. Fire and Emergency New Zealand (FENZ) should be consulted before any changes are made to the Acceptable Solution external fire spread FRR requirements.

8. Conclusions

A comparison of fire resistance ratings for a number of codes and standards from the United Kingdom (England, Wales and Scotland), USA, Canada and Australia has been made with the general requirements given in NZBC Acceptable Solutions C/AS5 and C/AS6. It was shown that, in many cases, the boundary wall fire ratings in C/AS5 and C/AS6 are significantly higher than would be the case for the equivalent situation in other comparable countries.

This study has applied a risk-based approach similar to that used in the United Kingdom in revising BS 9999:2017 and Approved Document B to recommend required fire resistance levels applicable to boundary walls in single-storey industrial and warehouse buildings. Parametric fire time temperature equations following EN 1991-1-2:2002 with modifications to account for roof venting were used to construct a fire severity model within an LHS simulation framework.

As expected, fire severity in industrial buildings with exposed roof structures permitting roof venting is shown to be lower compared to when venting is only available through vertical openings in the external wall. The proportion the simulations where roof venting was predicted to occur ranged from 25% (Case A) to 85% (Case C). In the cases where fire venting was predicted, the median time of venting, due to failure of the roof support structure, was consistently in the range 18–20 minutes. Engineered smoke/heat venting systems were not considered in the analysis, but if present, they would be expected to result in earlier venting.

For single-storey buildings within the scope of C/AS5, as might be represented by Case A, B, D and E in our analysis, the upper 80th percentile for the required fire resistance based on the t-e methodology ranged from 48 (Case A) to 79 minutes (Case B). It is suggested that adequate external fire spread protection could be achieved for unsprinklered industrial buildings without storage by 60 minute fire resistance rated boundary wall construction and 90 minutes for industrial buildings with up to 3 m high storage. Due to limitations on range of validity of inputs in the analysis method, the methodology may not be applicable for high fire load densities such as many warehouse buildings within the scope of C/AS6 or other buildings with more than a 3 m storage height and as represented by Case C in the analysis. The upper 80th percentile for the fire resistance for Case C based on the t-e methodology was determined to be 129 minutes (unsprinklered). While this should be treated with some caution due to the limitations of the analysis, it is considerably greater than the minimum fire resistance required for this type of occupancy in England, Wales, Scotland and Australia. It is, however, consistent with 120–180 minutes required by the IBC in the USA.

Where sprinklers are installed, fire resistance ratings can be modified by sprinkler reduction factors guided by Figure 51 depending on the reliability of the sprinkler and water supply.

Other limitations in the analysis apply to large area compartments where, in some cases, localised or travelling fires could lead to more severe heating conditions than those predicted by the parametric equations.

In all cases, the appropriate level of acceptable risk and design percentile values for building code compliance should be set by the regulatory body.

9. Future work

The methodology used in this study could be applied to other types of occupancy and be used to rationalise the level of fire resistance required by other Acceptable Solutions. The research could also be extended to include travelling fires in the methodology, although in the case of industrial buildings, current methods for travelling fires do not take into account the potential effects of roof venting.

Given current trends in warehouse design especially for higher rack storage, larger floor areas and portal spans, it would be valuable to gather more recent data on the typology of modern industrial and warehouse buildings including their area, height, wall openings, materials, fuel loads and storage heights.

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