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Fire spread from lower roofs project: Final report

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Preface

This is the final report of research into fire spread from lower roofs. This project is part of the larger BRANZ medium-density housing (MDH) research programme.

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BRANZ Study Report SR409

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Abstract

As New Zealand building densities increase, the potential for external fire spread and the impact of associated building regulations also increases. In particular, the recent push for higher-density housing results in more situations where external fire spread regulations are relevant. One such requirement is the '9 or 5' fire spread from lower roofs rule in the New Zealand Building Code clause C1–6 *Protection from fire* Acceptable Solutions and Verification Method. The justification for this rule has not been made clear. The influence of this rule on fire risk, which requires fire protection of either the wall adjacent to a lower roof (up to 9 m vertically above the roof) or the roof (up to 5 m horizontally from the wall) is not well quantified. This study report investigates requirements in other jurisdictions and existing research literature and provides comparisons with the current New Zealand regulations. The specific fire spread from lower roofs requirement in New Zealand does appear to be more conservative when compared to Australia, Canada, the US, the UK and Sweden. However, the general wall and roof requirements in other jurisdictions can override the specific requirements in some configurations and provide a similar or greater level of safety for this scenario. Potential heat fluxes on an adjacent external wall are estimated using flame height data and correlations and flame radiation models, and a series of reduced-scale experiments were conducted, with both categories of data compared to the prescriptive requirements.

Keywords

Flame spread, building regulations, fire, roofs, fire resistance, Acceptable Solutions, Verification Method, fire exposure.

Contents

Figures

Tables

1. Introduction

Increasing demand for New Zealand housing is driving a push towards higher-density housing in urban areas. Increased housing density with larger buildings closer together can potentially increase fire risk. Rezoning of existing residential areas is creating many situations where larger and taller multi-unit residential buildings are planned alongside existing housing stock.

Historically, the New Zealand Building Code (NZBC) Acceptable Solutions for protection from fire included specific requirements to prevent fire spread to external walls from an adjacent lower roof. Similar requirements were added explicitly in the July 2014 amendment of Verification Method C/VM2 *Framework for fire safety*. Subsequently, the Ministry for Business, Innovation and Employment (MBIE) has received numerous questions regarding clarification of these requirements.

Fires from roofs are not well understood but can be significant, as shown in Figure 1. A fire plume above a roof can be initiated either from a fire below penetrating the roof, ignition within the roof or ignition on the external surface of the roof. In the case of a fire below penetrating the roof, the buoyant plume from the fire below exits through an opening in the roof, which may be caused by failure of roof elements when exposed to the thermal conditions imposed by the fire.

Figure 1. July 2016 Sol Square fire in Christchurch.
Photo: Brian Dimbleby. Reproduced with permission.

Roof venting can also be intentional in fire conditions either through building design or fire service intervention (Figure 2), generally a North American fire service practice, to improve the environment in the compartment below.

Figure 2. Firemen simulate cutting into the roof of a house to vent fire and smoke. (U.S. Air Force. Photo by Dennis Carlson).

If the fuel vapour and heat generation in the fire is sufficient relative to the available oxygen in the compartment and the vertical distance above the seat of the fire, there will be flaming above the roof where fresh air becomes available to mix with unburnt fuel. If the roof has combustible elements, these will likely ignite and contribute to the flaming above the roof.

Regardless of the ignition scenario, a fire plume above a roof will impose a thermal insult on an adjacent external wall if present. Weather conditions (particularly wind) may influence the plume geometry and the resulting heat on the adjacent wall.

A historical example in New Zealand where fire spread from a lower roof resulted in substantial damage to a taller building occurred on 30 July 1978 in Hamilton's single-storey Bryce Street Market building, occupied as a flea market. Directly adjacent on opposing sides were the 2-storey Valentines Army Surplus store and 6-storey Rural Bank building (previously known as the State Advances building), which housed three government departments. Figure 3 shows the buildings prior to the fire.

The fire was reported in a *Waikato Times* article on 31 July 1978 (Reid, 1978):

> Fire chief Emrys Evans said the fire would probably have been quickly extinguished if a sprinkler had been installed.

On the damage to the 6-storey building, the article quotes Housing Corporation Deputy Lending Manager Ivan Morris:

> … it was fortunate the corporation's records of loan agreements were not in the file room, which was virtually destroyed in the blaze … flames burnt through the roof of the market, then licked up the wall of the six storey Rural Bank building beside it.

Figure 3. Buildings involved in the 1978 Bryce Street Market fire in Hamilton. Left to right, 2-storey Valentines building, single-storey Bryce Street Market, 6-storey Rural Bank building.
(Photo taken by Whites Aviation, 6 December 1972 (Whites Aviation, 1972). Ref: WA-70917-F. Alexander Turnbull Library, Wellington, New Zealand.)

The article describes the fire brigade actions and damage:

> A fireman on a turntable ladder battled to save the banking building. But flames swept up almost to the top before they were brought under control. The entire building was damaged by the intense heat. Even in areas the flames didn't reach plastic light covers sagged and paper turned crisp and brown. In the rest of the building telephones melted into blobs of plastic-coated metal and tables charred as if swept by a blowtorch. Government records were lost in the fire.

Figure 4 is a photograph from the *Waikato Times* article that demonstrates the building geometry involved, although it is difficult to discern the flames in the photo and it is unclear at which stage of the fire the photograph was taken.

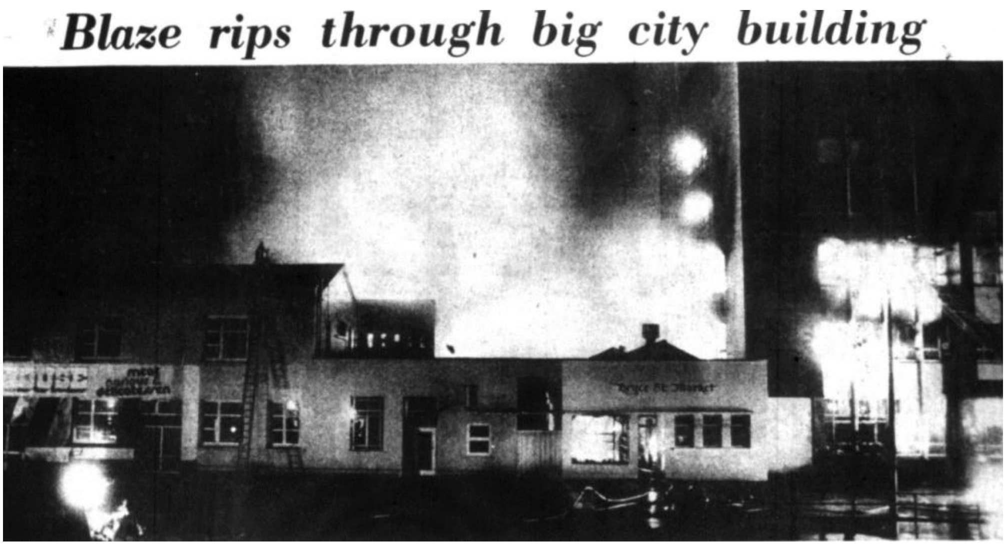

Figure 4. 1978 Bryce Street Market fire in Hamilton (Reid, 1978).
(Reproduced with permission from Fairfax.)

The fire load in the Bryce Street Market is unknown (although, as a flea market, it was likely to be high) and other details of the fire behaviour, progression and geometry are unclear and difficult to verify. However, the information available does provide an illustration of the fire spread from a lower roof scenario.

The 2005 Bracken Court fire in Dunedin is a more recent example. A fire started on the third (top) storey of an approximately 12 x 47 m brick warehouse that had been converted to residential and commercial occupancy. The fire occurred in the early afternoon on a workday and therefore the fire brigade was notified early.

Flames projecting from the roof and windows on the third storey impinged on the taller adjacent Evan Parry House as shown in Figure 5.

Figure 5. Bracken Court fire in Dunedin 2005.
(Photo: Ted Daniels. Reproduced with permission).

Windows in the 3 storeys of Evan Parry House above the roofline of the lower building were broken as shown in Figure 6.

Fire brigade access to the outside of Evan Parry House was limited, but crews were deployed inside and prevented further fire spread inside the taller building (Geddes, 2005). The fire service estimated the maximum flame height to be 12–15 m and indicated that fire spread within Evan Parry House occurred on five separate levels (Geddes, 2005).

Figure 6. Damage to adjacent building from 2005 Bracken Court fire in Dunedin.
(Channel 39, 2005. Reproduced with permission).

These examples demonstrate the potential for fire spread from lower roofs to occur.

This report initially reviews two aspects of fire spread from lower roofs. The first aspect is the current state of building regulations for fire spread from lower roofs in New Zealand and abroad. The second aspect reviews existing fire science research related to the topic to inform the experimental part of this project. The report also summarises a series of laboratory experiments and concludes by making several recommendations.

The intended outcomes of this project are to provide recommendations for fire spread from lower roofs requirements and/or methods to evaluate the thermal exposure from a roof fire in the NZBC Acceptable Solutions and Verification Method for protection from fire. The project will also provide fundamental technical rationale behind the recommendations. The scope of the BRANZ MDH programme, of which this project is part, is limited to residential buildings. However, the methods and results in this report are more widely applicable.

2. Regulatory requirements and guidance documents

A review of the current regulatory requirements in New Zealand and countries with similar building fire safety regulations is necessary to understand the current approach to managing fire spread from lower roofs. Section 2 discusses and compares overall performance requirements and specific fire spread from lower roofs prescriptive requirements in New Zealand, Australia, Canada, the UK and the US.

New Zealand has a hierarchical building regulation structure that has broad performance-based objectives at the top and pathways to demonstrate compliance with these objectives at the bottom (Figure 7). An introduction is included here to provide context for the fire spread from lower roofs requirements. The other countries discussed in this section have a similar tiered approach to building regulation with some variation, but this will not be discussed further in this report.

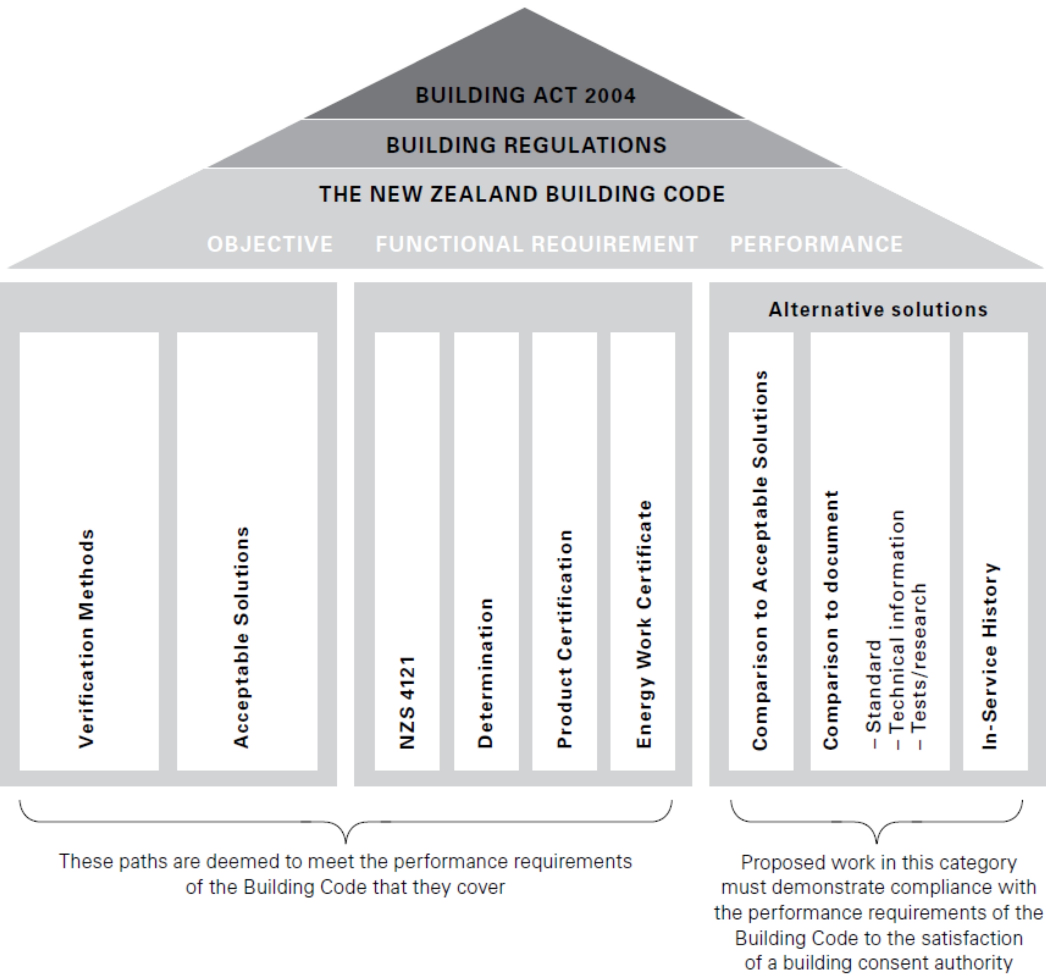

Figure 7. The structure of building regulations in New Zealand (MBIE, 2014c, p. 7).

The NZBC was implemented as the first national building code in New Zealand following the Building Act 1991. It comprised the first schedule of the Building Regulations 1992. In April 2012, a major revision to the NZBC protection from fire clauses was undertaken, along with the introduction of a Verification Method and a revamp of the Acceptable Solutions.

The NZBC clauses contain objectives, functional requirements and performance criteria (MBIE, 2014c). The NZBC requirements can be either satisfied by following Acceptable Solutions, Verification Methods or by proposing alternative methods based on engineering analysis (which become Alternative Solutions once accepted by the building consent authority). The aspects of the NZBC and supporting documents relevant for fire spread from lower roofs are included in the following sections.

International building code requirements that may affect how fire spread from lower roofs is considered in building design can also be either performance-based or prescriptive. Within the prescriptive requirements, there are two aspects that might influence fire spread from lower roofs to exterior walls: specific requirements for the configuration of having a lower roof adjacent to a higher exterior wall and the general requirements that are independent of the adjacent building configuration. If building regulations have more stringent general requirements for roofs and external walls, special requirements for the scenario of a lower roof adjacent to an external wall might not be warranted.

In the following sections, building code requirements in New Zealand, Australia, Canada, the UK and the US are compared based on three categories:

- Performance-based requirements.
- Specific fire spread from lower roofs requirements.
- General roof and external wall requirements.

2.1 Code performance requirements and verification methods

Performance requirements form the context of the prescriptive Acceptable Solution requirements and are necessary when doing specific engineering analysis of fire spread from lower roofs. This section reviews the relevant performance requirements and verification methods in the jurisdictions covered.

2.1.1 New Zealand

The NZBC originally included four fire safety clauses, which were qualitative in nature:

- C1 *Outbreak of fire*
- C2 *Means of escape*
- C3 *Spread of fire*
- C4 *Structural stability during fire*.

In April 2012, the fire safety clauses were reorganised into six clauses. The first clause C1 listed the overall objectives of the remaining five, summarised as:

- safeguarding people from fire
- protecting other property from fire
- facilitating firefighting and rescue operations.

The remaining five clauses provided the next tier of detail below the objectives, with the functional requirement and performance provisions:

- C2 *Prevention of fire occurring*
- C3 *Fire affecting areas beyond the fire source*
- C4 *Movement to place of safety*

- C5 *Access and safety for firefighting operations*
- C6 *Structural stability*.

The relevant clauses for external fire spread are discussed in the following section on the Verification Method.

Verification Method

Verification Method C/VM2 provides an optional means of compliance with NZBC clauses C1–C6 *Protection from fire* (MBIE, 2014b).

C/VM2 provides a range of design scenarios that must be considered and two relate to external fire spread:

- Design scenario 4.5 considers horizontal fire spread between neighbouring buildings or firecells.
- Design scenario 4.6 considers vertical fire spread on external walls.

Horizontal fire spread scenario

Design scenario 4.5 (HS) addresses horizontal fire spread between buildings. Relevant NZBC clauses are shown in Table 1.

Table 1. Code clauses cited for C/VM2 design scenario HS.

Code objective	C1(b)	Protect other property from fire.
Performance criteria	C3.6	Relevant boundary radiation from the building does not exceed 30 kW/m². Radiation from the building to 1 m beyond relevant boundary does not exceed 16 kW/m².
	C3.7	External wall materials closer than 1 m to the relevant boundary must either: • be non-combustible • not ignite for 30 min when subjected to 30 kW/m² radiant flux for importance level 3 and 4 buildings • not ignite for 15 min when subjected to 30 kW/m² radiant flux for importance level 1 and 2 buildings.
	C4.2	A means of escape must be provided so occupants of the building can move to a place of safety with low probability of unreasonable delay or impediment and will not suffer illness or injury as a result.
Required outcome	Demonstrate that C3.6 is met by calculating radiation from external wall unprotected areas and specify exterior cladding materials that meet C3.7. Control horizontal fire spread across a notional boundary to sleeping occupancies and exitways in buildings under the same ownership.	

While design scenario 4.5 does not specifically address fire spread from lower roofs, the purpose for including the information in this report is that the boundary radiation targets are useful for evaluating the heat flux generated from roof fires and the amount of heat insult an adjacent higher wall would be designed to withstand.

Vertical fire spread scenario

Design scenario 4.6 (VS) addresses vertical fire spread. In July 2014, Amendment 4 to C/VM2 added an additional Part C to design scenario 4.6 that specifically addresses fire spread from lower roofs. Relevant NZBC clauses are shown in Table 2.

Table 2. Code clauses cited for C/VM2 design scenario VS.

Code objective	C1(a)	Safeguard people from an unacceptable risk of injury or illness caused by fire.
	C1(b)	Protect other property from fire.
Performance criteria	C3.5	Buildings must be designed and constructed so that fire does not spread more than 3.5 m vertically from the fire source over the external cladding of multi-level buildings. This is to: • maintain tenable conditions on escape routes until occupants have evacuated • not compromise safety of firefighters working in or around the building.
Required outcome	Demonstrate that the building's external claddings do not contribute to excessive vertical fire spread using one of the methods described.	

There are three parts to be considered for the VS scenario:

- Part A: External fire spread over façade materials.
- Part B: Fire plumes spreading fire vertically up the external wall via openings and unprotected areas.
- Part C: Fire plumes spreading fire from a lower firecell through an unprotected lower roof to an adjacent higher external wall via unprotected areas.

There are no performance criteria in the NZBC that specifically address Part B and Part C. The performance criterion quoted in the VS scenario is only applicable to fire spread over cladding, while Part B and C address fire spread through unprotected openings. Previous BRANZ research (Collier, 2015; Frank, Park, Baker & Wade, 2018) has examined Part B. This report deals directly with Part C, which was added in an amendment to C/VM2 in July 2014.

The intention for Part C is described in C/VM2:

> The intention is to prevent fire from spreading from unsprinklered buildings due to a fire that has initiated below a non-fire rated lower roof that could spread to unprotected areas or openings that are located in a higher external wall.

Part C applies where there is a lower roof exposure to:

- external exitways
- sleeping occupancies behind a higher external wall within the same or an adjacent building
- other property behind a higher external wall within the same or an adjacent building.

The design fire exposure is specified as a:

> … fire plume spreading through a lower non fire rated roof to an adjacent higher external wall and spreading vertically via openings and unprotected areas in the same or adjacent building.

Methods of achieving the intentions of Part C are listed as:

a) Fire rating the underside of the lower roof where it represents an exposure risk to the higher external wall in order to prevent a fire plume extending through the lower roof, or
b) Fire rating parts of the higher external wall to prevent the fire plume that has passed through the unrated lower roof spreading into the higher levels, or
c) Installing sprinklers in the compartment below the unprotected lower roof.

Specific guidance on the extent of the fire rating for method a) and b) are referenced from Acceptable Solutions C/AS2–C/AS6 and are described in Appendix A.1. The fire resistance rating applied is to be based on the burnout fire for the space below the roof determined from C/VM2 paragraph 2.4.

2.1.2 Australia

The National Construction Code 2016 Volume One (ABCB, 2016) forms the Building Code of Australia for Class 2 to Class 9 buildings. Class 1 buildings are either single dwellings (attached or otherwise) or boarding type accommodation with total floor area less than 300 m² and less than 12 persons ordinarily resident. Class 2 buildings include those containing two or more sole-occupancy units, each being a separate dwelling, and Class 3 buildings are residential buildings other than a building of Class 1 or 2.

Performance requirements

Performance requirement CP2 addresses fire spread:

(a) A building must have elements which will, to the degree necessary, avoid the spread of fire—
  (i) to exits; and
  (ii) to sole-occupancy units and public corridors; and
  (iii) between buildings; and
  (iv) in a building.
(b) Avoidance of the spread of fire referred to in (a) must be appropriate to—
  (i) the function or use of the building; and
  (ii) the fire load; and
  (iii) the potential fire intensity; and
  (iv) the fire hazard; and
  (v) the number of storeys in the building; and
  (vi) its proximity to other property; and
  (vii) any active fire safety systems installed in the building; and
  (viii) the size of any fire compartment; and
  (ix) fire brigade intervention; and
  (x) other elements they support; and
  (xi) the evacuation time.

Verification Method

Verification Methods CV1 and CV2 provide a means of compliance with CP2(a)(iii). Compliance is verified when it is calculated to show that buildings "will not cause heat flux in excess of those set out in column 2 of Table CV1" (Table 3) for buildings on adjoining allotments and Table CV2 (Table 4) for buildings on the same allotment at the locations for the adjacent allotment or building as shown in column 1. Additionally, buildings must be capable of withstanding the heat flux values laid out in the same tables.

Table 3. Australia Building Code requirements for buildings on adjacent allotments (ABCB, 2016, Table CV1).

Location	Maximum heat flux (kW/m²)
On boundary	80
1 m from boundary	40
3 m from boundary	20
6 m from boundary	10

Table 4. Australia Building Code requirements for buildings on the same allotment (ABCB, 2016, Table CV2).

Distance between buildings	Maximum heat flux (kW/m²)
0 m	80
2 m	40
6 m	20
12 m	10

2.1.3 Canada

The National Building Code of Canada (CCBFC, 2015) uses the terminology of functional statements and 'objectives rather than performance criteria.

Functional statement

The relevant functional statement for walls exposed to adjoining roofs is F03, which states: "To retard the effects of fire on areas beyond its point of origin."

Objectives

The relevant objectives are:

> OS 1 *Fire safety*
>
> An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building or facility will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire addressed in this Code are those caused by …
>
> OS1.2 – fire or explosion impacting areas beyond its point of origin.
>
> OP1 *Fire protection of the building*
>
> An objective of this Code is to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by …
>
> OP1.2 – fire or explosion impacting areas beyond its point of origin.

2.1.4 United Kingdom

Requirement

The relevant requirement in the UK Building Regulations (HM Government, 2010) is as follows (Schedule 1, Part B Fire Safety):

> External Fire Spread
>
> B4.–(1) The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to the height, use, and position of the building.
>
> (2) The roof of the building shall adequately resist the spread of fire over the roof and from one building to another, having regard to the use and position of the building.

Performance

The UK Approved Document B (HM Government, 2013) states that the above requirements are deemed to be met:

> a. if the external walls are constructed so that the risk of ignition from an external source and the spread of fire over their surfaces, is restricted, by making provision for them to have low rates of heat release;
> b. if the amount of unprotected area in the side of the building is restricted so as to limit the amount of thermal radiation that can pass through the wall, taking the distance between the wall and the boundary into account; and
> c. if the roof is constructed so that the risk of spread of flame and/or fire penetration from an external fire source is restricted.
>
> In each case so as to limit the risk of a fire spreading from the building to a building beyond the boundary, or vice versa.
>
> The extent to which this is necessary is dependent on the use of the building, its distance from the boundary, and in some cases, its height.

2.1.5 United States

The International Building Code (IBC) (ICC, 2014) is primarily a prescriptive code but has some limited performance requirements. NFPA 101 (NFPA, 2015b) and NFPA 5000 (2015a) are model codes that can be adopted and include performance-based fire engineering design options.

IBC

The IBC lists performance requirements for external wall fire resistance in clause 1403.4: "Exterior walls shall be fire-resistance rated as required by other sections of this code with opening protection as required by Chapter 7."

A performance requirement for external wall vertical and lateral flame propagation is also included in clause 1403.5:

> Exterior walls on buildings of Type I, II, III, or IV construction that are greater than 40 feet (12 192 mm) in height above grade plane and contain a combustible water-resistive barrier shall be tested in accordance with and comply with the acceptance criteria of NFPA 285.

Types of construction are listed in Table 32.

NFPA 101 and NFPA 5000

NFPA 101 and NFPA 5000 include the following relevant safety from fire objective:

> Buildings shall be designed and constructed to protect occupants not intimate with the initial fire development for the time needed to evacuate, relocate, or defend in place.

NFPA 5000 also includes an objective that states:

> Buildings shall be designed and constructed to reasonably protect adjacent persons and buildings from injury, death, or substantial damage as a result of a fire.

NFPA 101 and NFPA 5000 have similar design scenarios to C/VM2, albeit more qualitative and less specific. Design fire scenario 7, which is an outside exposure fire:

> … shall address the concern regarding a fire starting at a location remote from the area of concern and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area.

2.1.6 Scandinavia

INSTA TS 950 (INSTA, 2014) is a comparative verification method that has been adopted in Denmark, Finland, Iceland, Norway and Sweden. The objective is stated as:

> … the construction works must be designed and built in such a way that in the event of an outbreak of fire … occupants can leave the construction works or be rescued by other means …

The recommended comparative analysis involves proving that:

> … the risk of fire spread for the trial design is less than for a reference case where pre-accepted minimum separation distances are used … Consideration shall be taken to the size of fire compartments, openings, and the placement of adjacent buildings.

A fixed evaluation criteria is also recommended for materials with "reaction to fire class worse than A2-s1,d0". The recommended criteria is 15 kW/m² of received radiation for 30 minutes, calculated at 30 s averages. Emitted radiation recommendations are provided for fixed radiation from unprotected areas – 84 kW/m² in residential, office, assembly or recreational type buildings or 168 kW/m² for shops, commercial, industrial, storage and other non-residential type buildings – and for flames from windows.

2.1.7 Summary

All of the jurisdictions considered have performance-based requirements that should cover the potential for fire spread from lower roofs. They range from broad fire safety objectives (in most cases) to more specific requirements in the case of C/VM2. It is difficult to evaluate how these performance-based requirements are followed in practice without looking at specific building designs.

2.2 Prescriptive requirements

The following section lists specific prescriptive fire spread from lower roofs requirements in the jurisdictions covered.

2.2.1 New Zealand

This section looks at both the current requirements and the history of the requirements for fire spread from lower roofs in the New Zealand Acceptable Solutions for the fire safety clauses to investigate when and why the requirements were added.

Current requirements

As of April 2012, the New Zealand Acceptable Solutions for the fire safety clauses were split up by major occupancy classifications as shown in Table 5.

Table 5. New Zealand protection from fire Acceptable Solutions.

Acceptable Solution	Risk Group	Description	Prescriptive requirement?	Paragraph 2.3 FRR*
C/AS1	SH	Detached houses and multi-unit residential buildings with either independent escape routes to a safe place from each dwelling or no more	Yes	L: 30 min P: 30 min
C/AS2	SM	All multi-unit accommodation not included in SH.	Yes	L: 60 min* P: 60 min*
C/AS3	SI	Detention or care facilities (occupants incapacitated, unable to evacuate unaided, or delayed in evacuation)	No	
C/AS4	CA	Crowd and assembly occupancies	Yes	L: 60 min* P: 120 min*
C/AS5	WB	Commercial occupancies with low to medium risk	Yes	L: 60 min* P: 120 min*
C/AS6	WS	High risk occupancies	No	
C/AS7	VP	Vehicle storage	Yes	120 min **

***L: life rating, P: property rating**

**** Indicates that sprinklering (or Type 7 alarm system for C/AS2) reduces the required FRR by 50%.**

***** C/AS7 includes a requirement for a higher external wall within 3.0 m vertically and 1.5 m horizontally of a roof used for car parking to be fire rated to 120/120/120.**

The requirements for fire rating either lower roofs or adjacent higher exterior walls in the New Zealand Acceptable Solutions are shown in Figure 8.

There are essentially two options: fire rate 9 m of the vertical wall above the lower roof (with no unprotected areas) or the adjacent 5 m of the lower roof.

The fire rating of either the wall or roof must also extend laterally 5 m past the extremity of the other. Alternatively, no fire rating is required if the fire cell below the lower roof is sprinklered.

The required fire resistance rating is given in paragraph 2.3 of the relevant Acceptable Solution document and listed in Table 5.

This requirement is included in C/AS1, C/AS2, C/AS4 and C/AS5.

There is also a separate requirement in C/AS7 for the case where there is roof vehicle car parking. If the:

… roof used for vehicle car parking is within 1.5 m of a higher external wall and the adjacent building above contains sleeping risk groups, external wall protection above the adjacent lower roof shall be provided by constructing the critical part of the wall (that closer to the roof than 3.0 m vertically or 1.5 m horizontally) with an FRR of no less than 120/120/120.

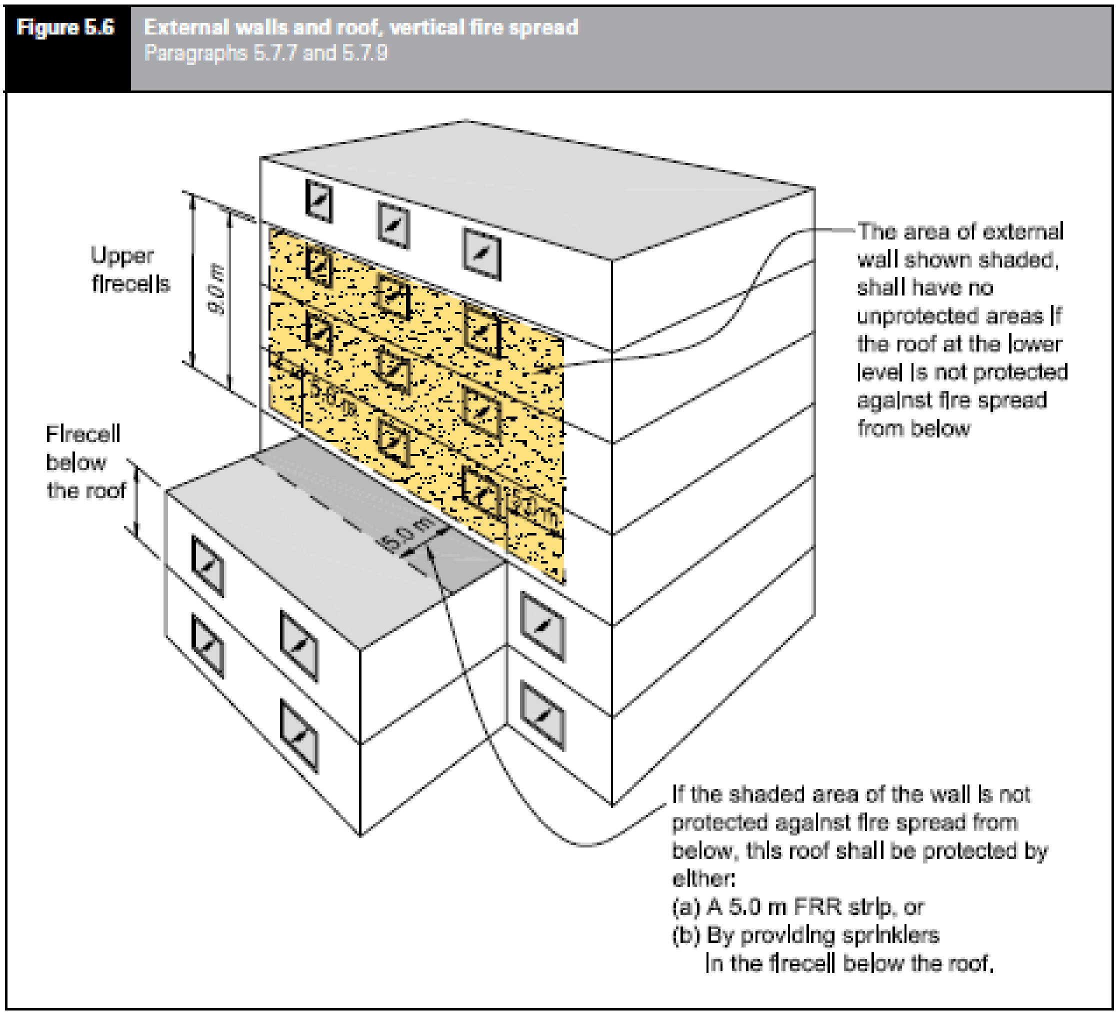

Figure 8. C/AS requirements for prevention of fire spread from lower roofs (MBIE, 2014a, p. 98).

Historical requirements

Similar requirements for fire spread from lower roofs have been in place since the first Acceptable Solutions for the NZBC were introduced in 1992.

The relevant sections from the July 1992 version of C3/AS1 spread of fire Acceptable Solution are as follows:

> 4.4 Vertical Fire Spread
>
> 4.4.1 Fire spread from an adjacent lower roof
>
> Fire spread from a roof close to and lower than an external wall shall be avoided by compliance with Paragraph 4.4.2 where firecells behind the wall contain:

> a) Purpose Groups SC, SD, SA, SR, or CM in the same building or an adjacent building on the same title, or
>
> b) Any purpose group in an adjacent building on other property.
>
> 4.4.2 Where the distance between any part of an external wall is less than 9.0 m vertically or 5.0 m horizontally, protective measures shall be applied either to the roof as in Paragraph 4.4.3, or to the wall as in Paragraph 4.4.4.
>
> 4.4.3 Roof protection shall be provided by:
>
> a) Installation of sprinklers in the firecell below the roof, or
>
> b) Constructing that part of the roof within 5.0 m horizontally of the wall, with a FRR of:
>
> i) 30/30/30 or the S rating where required by Table 1, whichever is the greater, where the fire hazard category is less than 3 in the firecell below the roof.
>
> ii) 60/60/60 or the S rating when required by Table 1, whichever is the greater, where the fire hazard category is 3 or more in the firecell below the roof.
>
> 4.4.4 External wall protection above an adjacent lower roof shall be provided by:
>
> a) Constructing the critical part of the wall (closer to the roof than 9.0 m vertically or 5.0 m horizontally) with a FRR of no less than required in Paragraph 4.4.3 (b), and
>
> b) Having no unprotected areas within:
>
> i) The critical area, (except that in purpose groups WL, CS or CM the small amount of unprotected area allowed by Method 1 of Appendix C may be installed), or
>
> ii) An area of the wall closer to a lower roof than 3.0 m vertically and 2.0 m horizontally, and installing thermally operated automatic drenchers on any unprotected areas outside that area.

Purpose groups and their associated fire hazard categories are shown in Table 6.

Section 4.0 in the July 1992 Acceptable Solution document notes that:

> These requirements for external walls and roofs have been adapted from Building Regulations 1985 (England and Wales), and Approved Document B4 “External Fire Spread” 1990, with the permission of the controller of HMSO.

Table 6. C/AS crowd and sleeping activity purpose groups and associated fire hazard categories at the time the NZBC Acceptable Solutions were introduced in July 1992.

Table 2.1: Purpose Groups
Paragraphs 1.3.4, 2.1.3, 2.2.1, 2.2.10, 5.6.10 and 5.6.12

Purpose group	Description of intended use of the building space	Some examples	Fire hazard category
CROWD ACTIVITIES			
CS or CL	For *occupied spaces*. CS applies to *occupant loads* up to 100 and CL to *occupant loads* exceeding 100.	Cinemas when classed as CS, art galleries, auditoria, bowling alleys, churches, clubs (non-residential), community halls, court rooms, dance halls, day care centres, gymnasia, lecture halls, museums, eating places (excluding kitchens), taverns, enclosed grandstands, indoor swimming pools.	1
		Cinemas when classed as CL, schools, colleges and tertiary institutions, libraries (up to 2.4 m high book storage), nightclubs, restaurants and eating places with cooking facilities, *theatre* stages, opera houses, television studios (with audience).	2
		Libraries (over 2.4 m high book storage).	3
CO	Spaces for viewing open air activities (does not include spaces below a grandstand).	Open grandstands, roofed but unenclosed grandstand, uncovered fixed seating.	1
CM	Spaces for displaying, or selling retail goods, wares or merchandise.	Exhibition halls, retail shops.	2
		Supermarkets or other stores with bulk storage/display over 3.0 m high.	4
SLEEPING ACTIVITIES			
SC	Spaces in which *principal users* because of age, mental or physical limitations require special care or treatment.	Hospitals. Care institutions for the aged, children, *people with disabilities*.	1
SD	Spaces in which *principal users* are restrained or liberties are restricted.	Care institutions, for the aged or children, with physical restraint or detention. Hospital with physical restraint, detention quarters in a police station, prison.	1
SA	Spaces providing transient accommodation, or where limited assistance or care is provided for *principal users*.	Motels, hotels, hostels, boarding houses, clubs (residential), boarding schools, dormitories, halls, *wharenui*, community care institutions.	1
SR	Attached and multi-unit residential dwellings.	*Multi-unit dwellings* or flats, apartments, and includes *household units* attached to the same or other *purpose groups*, such as caretakers' flats, and residential accommodation above a shop. *Household unit firecells* may contain garages which are used exclusively by the occupants of that *household unit*.	1
SH	Detached dwellings where people live as a single household or family.	Dwellings, houses, being *household units*, or *suites* in *purpose group* SA, separated from each other by distance. Detached dwellings may include attached self-contained *suites* such as granny flats when occupied by a member of the same family, and garages whether detached or part of the same *building* and are primarily for storage of the occupants' vehicles, tools and garden implements.	1

Prior to the introduction of the NZBC in 1992, there was no national building code in New Zealand. Rather, New Zealand Standard (NZS) 1900 was available as a model building code and could be adopted by municipal authorities. NZS 1900 Chapter 5:1988 *Fire Resisting Construction and Means of Egress* did not include a similar fire spread from lower roofs clause.

However, clause 5.10.2 did allow buildings to have a larger ground floor podium floor area compared to upper floor areas provided that the "roof of the excess area shall have a FRR of not less than that required for the corresponding floor at that level". This is shown in Figure 9, from a 1982 illustrated guide to NZS 1900 Chapter 5:1963 (NZFS Commission, 1982).

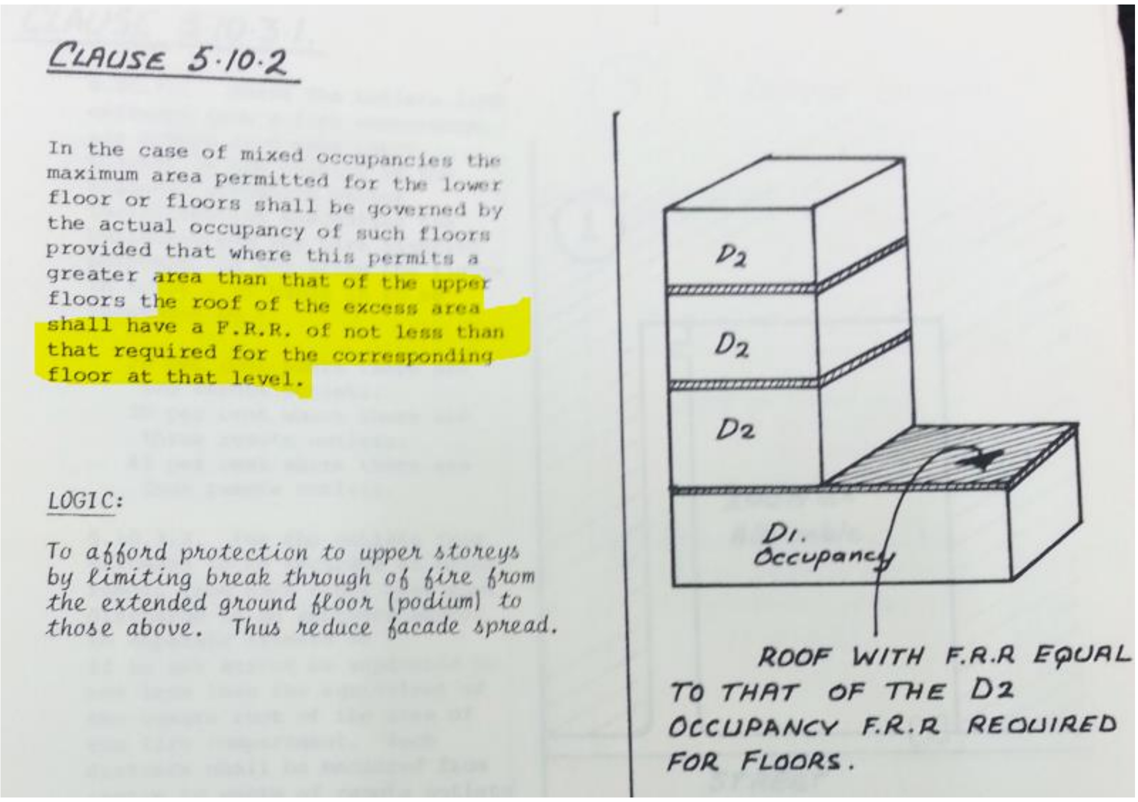

Figure 9. Requirement for excess ground floor roof area (NZFS Commission, 1982).
(Reproduced with permission)

DZ 4226:1984 *Design for fire safety* was a draft New Zealand standard intended to provide a replacement for Chapter 5 of the NZS 1900:1963 and also a "code of practice for design for fire safety". It does not appear that DZ 4226:1984 was ever finalised and the changes were not included in Chapter 5 of NZS 1900:1988. The preliminary notes of the draft document included the statement of a need for a record of the basis of reasoning behind the provisions, which was subsequently provided by BRANZ (Bastings, 1988).

Part 4 of DZ 4226:1984 specifically targeted "fire emerging from windows, and heat radiating from the surface of a fire compartment". It noted that:

> … flames and heat radiation need to be considered not just in the horizontal direction, from wall to wall, but also vertically, when the lower of two adjacent, or adjoining, fire compartments can set fire to its higher neighbour.

Bastings (1988) notes that "the danger of spread from a lower roof to a higher adjacent fire compartment" was one of two problems "not dealt with adequately in existing codes".

DZ 4226:1984 proposed the following requirements to prevent fire spread from lower roofs:

> C4.3.1.1 Construction having the specified fire resistance rating will permit neither radiation of heat energy nor flame protrusion for the fire duration and is not controlled by this Part (Radiating areas will not permit flame protrusion and need comply only with section 4.3). Openings, and substandard construction however, permit the passage of both 100% radiation and flame, and must comply with this section.
>
> For the purposes of the following clauses, openings and substandard construction have been divided into two groups:
>
> i. Vertical: including windows, doors, and the open sides of balconies, and the like, in the vertical planes of the enclosing envelope;
> ii. Horizontal and inclined: including sloping windows, open light wells, and roof areas close to an adjacent fire compartment.
>
> Exposing faces includes roofs, which, when unrated, must be classed as substandard construction or as radiating surfaces (when allowing radiation alone). It is necessary to allow for the hazards of fire through unrated roof areas when another fire compartment, or another storey of the same fire compartment, may be exposed.

DZ 4226:1984 proposed a boundary of flame projection from a horizontal opening as shown in Figure 10. DZ 4226:1984 Schedule 4.2A lists dimensions equivalent to those in Figure 10 as minimum flame separation distances and notes:

> … unless protected by a specific fire safety measure, no opening or substandard construction in an exposing face is permitted within these distances. Fire safety measures are set out in clauses 4.2.2 and 4.2.3. The necessity to comply with this requirement may be avoided by use of fire resistant glazing. The distances are from NFPA 80a, and are 6 m normal to, and either side of an opening, and 10 m above it.

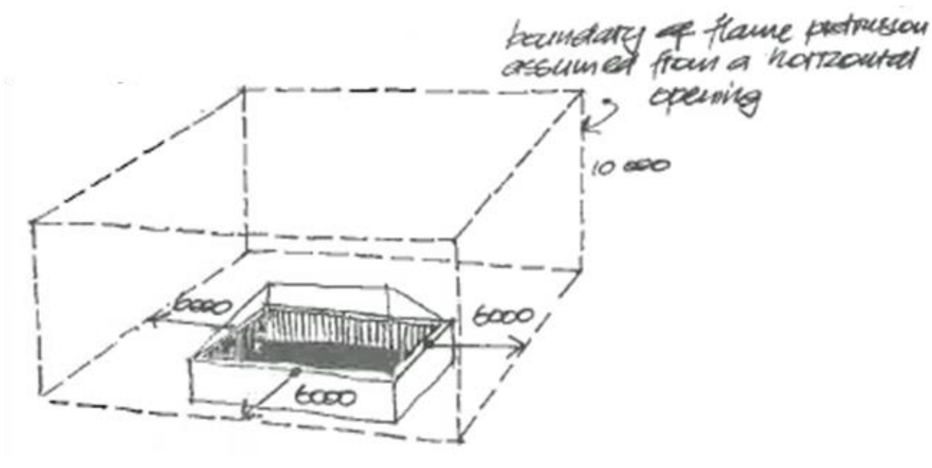

Figure 10. DZ 4226:1984 boundary of flame protrusion assumed from a horizontal (roof) opening.

DZ 4226:1984 continues:

> 4.2.3.2 Openings and substandard construction in exposed faces of storeys at upper levels shall be protected from flame protrusion through horizontal or inclined planes of exposing faces at lower levels by either:

> a. Fire windows no greater in area that [sic] 10% of any exposed face, to a height of at least 10 m above the fire load ceiling of the storey with the exposing face, except that, where the flame separation distance is between different fire compartments, the fire windows shall be also protected by external drenchers.
> b. The plane of the lower exposing face is constructed as a radiating surface of the appropriate FRR, for a horizontal distance of 6 m from the plane of the upper exposed face.
>
> C4.2.3.2 See D4.2.3.2 (Figure 11). It should be carefully understood that these requirements can only apply to fire compartments in the one ownership. That is, one owner cannot, through this Code, compel an adjoining owner to take precautions against the fire hazards presented by the first owner's building. But, each individual owner has a duty to protect any adjoining or adjacent fire compartment from spread of fire to it, whether that neighbouring fire compartment belongs to that owner, or somebody else. However, this clause also provides for one fire compartment to be protected from a non-complying adjacent fire compartment. If the latter is in the same ownership as the former, then there is no question that these requirements must be met. But, if the latter is not in the same ownership as the former and is a previously existing building, then the fire hazard presented by the latter is one that can only be coped with voluntarily by the owner of the former. This problem should be carefully considered when unit titles are being used to subdivide a lot into separate ownerships, and is recommended that in such situations, each fire compartment under separate ownership be designed to protect any future adjoining fire compartment from spread of fire to it.

The definition of a radiating surface is given by Bastings (1988) as "construction that contains all the effects of fire, other than radiation, for a specified time". He goes on to explain that:

> ... the definition was seen as needed to cover such common construction as metal-clad factories and warehouses, where the walls or roof do not have a FRR in terms of all the three conventional criteria, but are able to resist flame protrusion for a calculable or testable period. (Note that "fire window" is defined as a special case of a "radiating surface").

DZ 4226:1984 makes this explicit as:

> … radiating surfaces are required to have a FRR, but only when determined by criteria for stability and integrity, not insulation. Therefore that FRR applies equally to their supporting structure. Fire windows made with normal wired glass, and many sheet metal cladding systems, are both deemed to have a 1 hr FRR, if conforming to an approved specification listed in the Schedule of Approvals.

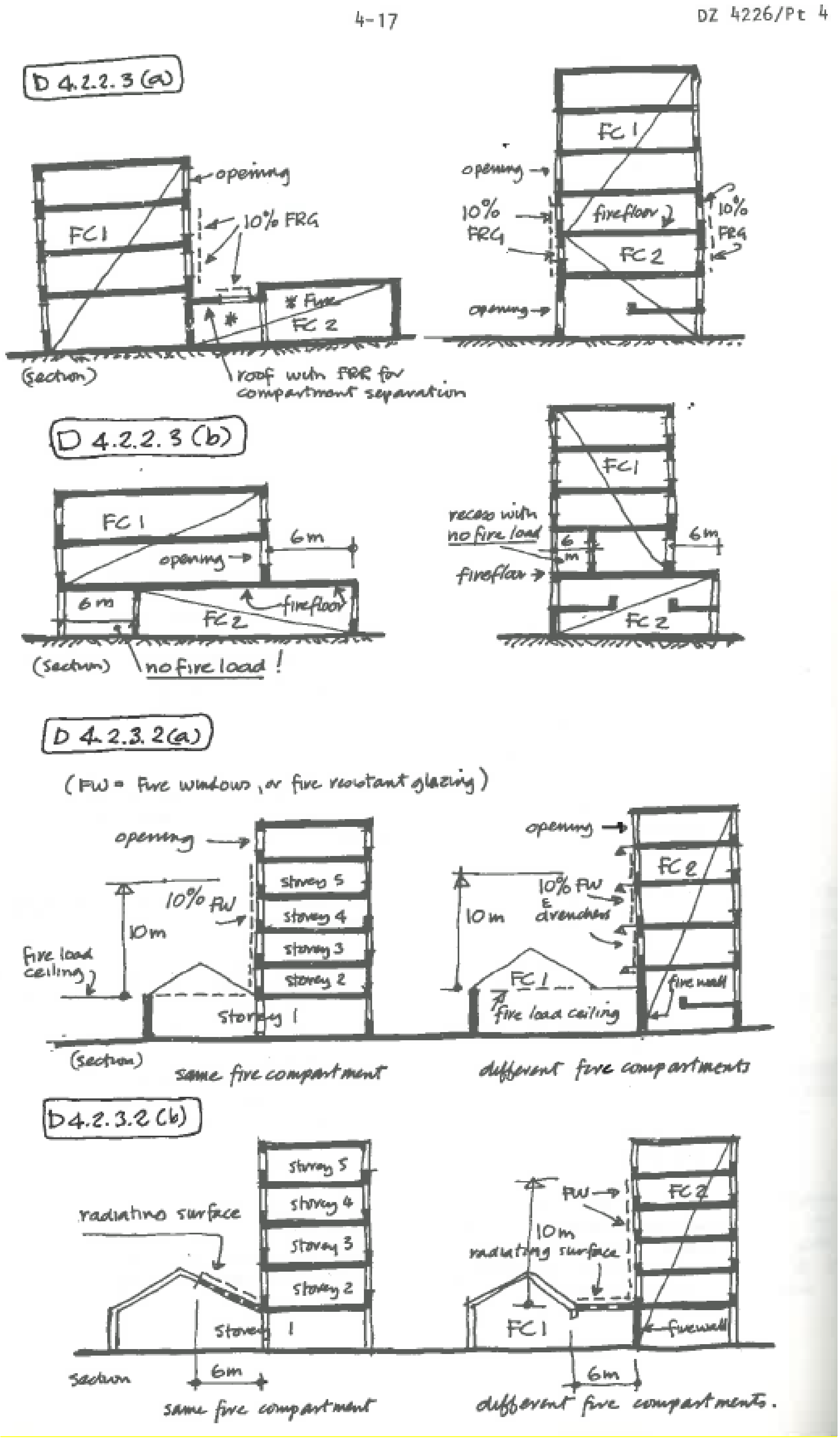

Figure 11. DZ 4226:1984 fire from lower roofs scenario illustrations.

Section 5.2.3.5 lists the requirements for FRR at compartment separations, including:

> where any compartment separation … passes by the roof of either fire compartment:
>
> and (a) the roofs of each adjoining fire compartment are in the same plane, or there is less than 3 m difference in height between the two planes;
>
> then (b) for a distance of 3 m either side of the compartment separation, or for a distance of 6 m on one side of the compartment separation, either:
>
> i. The roof shall be constructed as a radiating surface with half the FRR of the compartment separation; or
> ii. The roof shall be lined on the underside of the framing with thermal barrier materials in accordance with an approved specification, with fire stops at any exposed edge of the cavity between the thermal barrier linings and the roofing material, to achieve an approved degree of resistance against flame penetration;
>
> and (c) in neither case do the structural elements directly supporting the roof assembly require to have more than half the FRR of the compartment separation, or a 1 hr FRR, whichever is the less;
>
> and (d) this requirement shall not apply when either roof assembly for at least the distance specified, is either:
>
> i. Totally in non-combustible construction, with an exterior cladding which is also non-combustible; or
> ii. Constructed with an FRR equal to half the FRR of the compartment separation; or
> iii. When the requirements of Part 4 for flame separation distances have otherwise been complied with, or
> iv. When both compartments are protected by a sprinkler system.
>
> C5.2.3.5 The purpose of this requirement is to stop flames protruding up through a roof of one fire compartment penetrating the roof of an adjoining fire compartment. Vertically, flames can reach up to 10 m height, and horizontally they are considered a hazard up to 6 m. However, allowance has been made for a probable reduction in flame temperature to half of that of the fire intensity.
>
> Exp.5.2.3.5 There was disagreement over the nature of provision that this requirement should specify. The majority view was that the flame separation limits of Part 4 should be taken as the criterion, and that basis has been used for this clause; also bearing in mind the majority view that parapets are of no real benefit in controlling this hazard unless unacceptably high, and that they were a considerable nuisance, in any case, for other reasons. The strongly held minority view was that traditional parapet provisions, such as those in the Canadian Building Code were more desirable, and possibly less costly, and could be presumed to be satisfactory for coping with this hazard if, say 300 mm [sic] high where a 2 hr FRR required for the compartment separation, or 900 mm high for any greater FRR; and that no precaution was necessary where the FRR was 1 hour or less. The proposal is therefore open to comment from those with experience of the actual hazard, and the extent it needs controlling.

2.2.2 Australia

The Australian Building Code (ABCB, 2016) has the following specific requirement for walls next to lower roofs (specifically relevant sections are shaded):

> C2.7 Separation by fire walls
>
> (b) Separation of Buildings—A part of a building separated from the remainder of the building by a fire wall may be treated as a separate building for the purposes of the Deemed-to-Satisfy Provisions of sections C, D, and E if it is constructed in accordance with (a) and the following:
>
> (i) The fire wall extends through all storeys and spaces in the nature of storeys that are common to that part and any adjoining part of the building.
>
> (ii) The firewall is carried through to the underside of the roof covering.
>
> (iii) Where the roof of one of the adjoining parts is lower than the roof of the other part, the fire wall extends to the underside of—
>
> (A) the covering of the higher roof, or not less than 6 m above the covering of the lower roof; or
>
> (B) the lower roof if it has an FRL not less than that of the fire wall and no openings closer than 3 m to any wall above the lower roof; or
>
> (C) the lower roof if its covering is non-combustible and the lower part has a sprinkler system complying with Specification E1.5.

2.2.3 United Kingdom

The UK Approved Document B (HM Government, 2013) provides acceptable solutions for fire safety. Approved Document B only requires roofs to be fire-rated from the underside if any part forms an escape route or any roof performs the function of a floor.

A reference is made to a reaction-to-fire requirement for an external wall next to a lower roof in Diagram 40 (Figure 12). This requirement is for assembly or recreation buildings exceeding 1 storey for "up to 10 m above a roof or any part of the building to which the public have access." The flame spread requirement is an index less than or equal to 20 as tested to BS 476-6:1989+A1:2009 *Fire tests on building materials and structures. Method of test for fire propagation for products* or a European class C-s3, d2, or better. There is no requirement for the adjacent roof itself.

This requirement was essentially unchanged from the 1992 Approved Document B, other than the addition of the European classes. The previous 1985 Approved Document B had some slight differences. The height requirement was 7.5 m rather than 10 m. Also, unprotected areas were limited as shown in Figure 13.

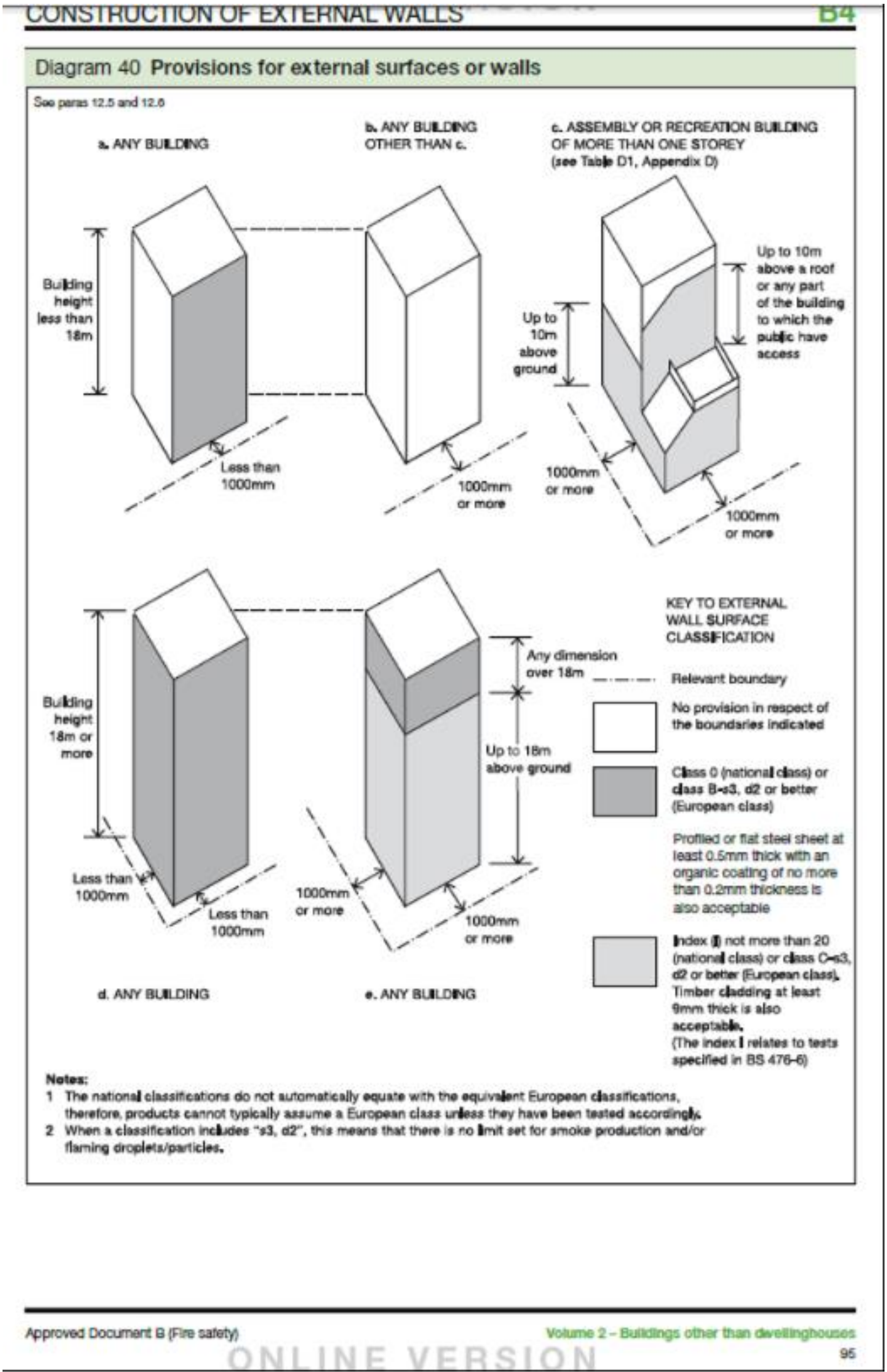

Figure 12. UK Approved Document B provisions for external surfaces or walls.
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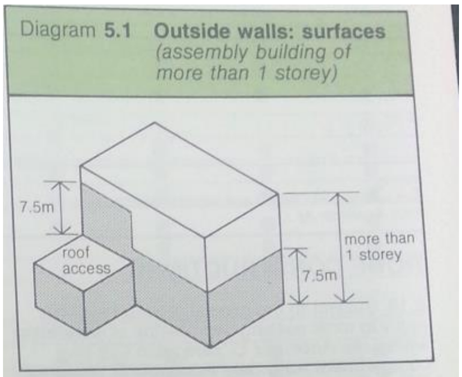

Notes

1 Unprotected areas in shaded part to be limited to:
(a) doors, or
(b) other openings that would enable persons inside the building to be aware of any fire that might start outside the building.

2 Surfaces of shaded part, including any glazed opening (but not any door or any frame for a door or glazing) to have:
(a) if less than 1m from any point on the relevant (or notional) boundary: a Class 0 surface
(b) if 1m or more from the boundary: fire propagation index (I) not more than 12 and sub-index (i_1) not more than 6.

3 Special provisions apply to fire resistance of shaded part if 1m or more from relevant boundary. *(see Appendix A, Table A1, item 4(b))*

4 Unprotected areas in unshaded part to meet provisions in Appendix J.

5 Cladding of unshaded part to meet provisions in Table 5.2.

Figure 13. Requirements for walls above lower roofs from UK Approved Document B 1985.
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2.2.4 Canada

The National Building Code of Canada has the following specific requirements:

> 3.2.3.15 Wall Exposed to Adjoining Roof
>
> 1) Except as permitted by Sentence 3.2.3.19.(4), if a wall in a building is exposed to a fire hazard from an adjoining roof of a separate fire compartment that is not sprinklered in the same building, and the exposed wall contains windows within 3 storeys vertically and 5 m horizontally of the roof, the roof shall contain no skylights within 5 m of the exposed wall.
>
> 3.2.3.19.(4) A walkway of non-combustible construction used only as a pedestrian thoroughfare need not conform to the requirements of Articles 3.2.3.14 and 3.2.3.15.

2.2.5 United States

The United States 2015 International Building Code (ICC, 2014) is a model building code that is adopted in some jurisdictions. The IBC is primarily a prescriptive building code (specifically relevant sections are shaded).

> 705.8.6 Vertical exposure. For buildings on the same lot, opening protectives having a fire protection rating of not less than ¾ hour shall be provided in every opening that is less than 15 feet (4572 mm) vertically above the roof of an adjacent building or structure based on assuming an imaginary line between them. The opening protectives are required where the fire separation distance between the imaginary line and the adjacent building or structure is less than 15 feet (4572 mm).

Exceptions:

1. Opening protectives are not required where the roof assembly of the adjacent building or structure has a fire resistance rating of not less than 1 hour for a minimum distance of 10 feet (3048 mm) from the exterior wall facing the imaginary line and the entire length and span of the supporting elements for the fire-resistance-rated roof assembly has a fire-resistance rating of not less than 1 hour.

2. Buildings on the same lot and considered as portions of one building in accordance with Section 705.3 are not required to comply with Section 705.8.6.

706.6 Vertical continuity. Fire walls shall extend from the foundation to a termination point not less than 30 inches (762 mm) above both adjacent roofs.

Exceptions:

1. Stepped buildings in accordance with Section 706.6.1.

2. Two-hour fire-resistance-rated walls shall be permitted to terminate at the underside of the roof sheathing, deck, or slab, provided:
   2.1 The lower roof assembly within 4 feet (1220 mm) of the wall has not less than a 1-hour fire-resistance rating and the entire length and span of supporting elements for the rated roof assembly has a fire resistance rating of not less than 1 hour.

   2.2 Openings in the roof shall not be located within 4 feet (1220 mm) of the fire wall.

   2.3 Each building shall be provided with not less than a Class B roof covering.

3. Walls shall be permitted to terminate at the underside of non-combustible roof sheathing, deck, or slabs where both buildings are provided with not less than a Class B roof covering. Openings in the roof shall not be located within 4 feet (1220 mm) of the fire wall.

4. In buildings of Type III, IV, and V construction, walls shall be permitted to terminate at the underside of combustible roof sheathing or decks, provided:
   4.1 There are no openings in the roof within 4 feet (1220 mm) of the fire wall.

   4.2 The roof is covered with a minimum Class B roof covering, and

   4.3 The roof sheathing or deck is constructed of fire-retardant-treated wood for a distance of 4 feet (1220 mm) on both sides of the wall or the roof is protected with 5/8 inch (15.9 mm) Type X gypsum board directly beneath the underside of the roof sheathing or deck, supported by not less than 2-inch (51 mm) nominal ledgers attached to the sides of the roof framing members for a distance of not less than 4 feet (1220 mm) on both sides of the fire wall.

> 706.6.1 Stepped Buildings. Where a fire wall serves as an exterior wall for a building and separates buildings having different roof levels, such wall shall terminate at a point not less than 30 inches (762 mm) above the lower roof level, provided the exterior wall for a height of 15 feet (4572 mm) above the lower roof is not less than 1-hour fire-resistance-rated construction from both sides with openings protected by fire assemblies having a fire protection rating of not less than ¾ hour.
>
> Exception: Where the fire wall terminates at the underside of the roof sheathing, deck, or slab of the lower roof, provided:
>
> 1. The lower roof assembly within 10 feet (3048 m) of the wall has not less than a 1-hour fire-resistance rating and the entire length and span of supporting elements for the rated roof assembly has a fire-resistance rating of not less than 1 hour.
> 2. Openings in the lower roof shall not be located within 10 feet (3048 mm) of the fire wall.

2.2.6 Sweden

The Swedish building regulations provide a general recommendation for the "protection against fire spread to a fire compartment located above an adjacent roof" (Boverket, 2016):

> Protection can, for example, be maintained through a combination of protective distance, separating structures, radiation protection and non-combustible roof covering. Examples of acceptable solutions could be that,
>
> - The exterior wall to the higher situated fire cell, including windows, up to a height of 5 meters above the adjacent roof is given a fire-resistance equal to the requirement of the separating structure. However, for windows that make up less than 20 % of the affected area, fire resistance class EW 30 is accepted.
> - The adjacent roof at a distance of less than 8 meters from the exterior wall is given a fire resistance equivalent to REI 60. If all adjacent fire compartments have separating structures and load bearing capacity in case of fire for not more than 30 minutes, REI 30 can be accepted.
> - An automatic water sprinkler system is installed in lower lying spaces. (BFS 2014:3).

2.2.7 Summary

A summary of the specific prescriptive requirements for fire spread from lower roofs in New Zealand, Australia, Sweden, the US, Canada and the UK is shown in Table 7.

New Zealand, Australia, Sweden and the US all specify fire resistance for these circumstances while Canada only limits openings in the roof and the UK only considers the reaction to fire for assembly occupancy buildings. However, if a jurisdiction has more stringent requirements for roofs or external walls in general, additional requirements for these specific circumstances may not be as necessary.

Table 7. Summary of specific building regulation requirements for lower roofs for New Zealand, Australia, Sweden, the US, Canada and the UK.

Country	Document	External Wall	Lower Roof	Requirement
New Zealand	C/AS1,2,4,5	9.0 m	5.0 m	FRR which varies depending on acceptable solution
Australia	National Construction Code	6.0 m	3.0 m	Same FRR as lower firewall
Sweden	Boverket's Building Regulations (English Translation)	5.0 m	8.0 m	Exterior wall: FRR equal to requirement of separating structure (up to 20% of area can be windows with 30 min integrity and radiation FRR) Roof: 60 min FRR
USA	IBC 2015	4.6 m*	3.0 m	1 hour FRR with 45 min protective assemblies on openings
Canada	National Building Code	-	5 m	No skylights in roof if windows are within 3 storeys vertically and 5 m horizontal to roof
UK	Approved Document B	10 m		Reaction to fire for assembly buildings (no FRR)

*Note: IBC 2015 external wall requirement is required if the lower roof requirement is not met and there is a fire separation distance of 4.6 m or less.

2.2.8 Related general external fire spread prescriptive requirements

The need for specific fire spread from lower roofs prescriptive requirements can be influenced by the level of generic external roof and wall fire protection required. The relevant general external fire spread prescriptive requirements in each jurisdiction considered in the above section are included in Appendix A.

2.3 Additional guidance documents

2.3.1 NFPA 80A

NFPA 80A (NFPA, 2017) is a ”recommended practice for fire protection of buildings from exterior fire exposures”. Section 4.3.8 Exposure from Buildings of Lesser Height, has the following recommendations:

> 4.3.8.1 Where the exposing building is of lesser height than the exposed building, the separation distance first should be determined from Table 4.3.7.3 (used to determine separation distances based on percentage of unprotected openings in walls).
>
> 4.3.8.2 Where the roof assembly of the exposing building is combustible and has no fire resistance rating, means of protection should be provided above the roof level of the exposing building in accordance with Table 4.3.8.2.
>
> 4.3.8.3 Where separation distances derived from Table 4.3.7.3 do not exceed the distances indicated in Table 4.3.8.2 (Table 1), means of protection should be applied on the exposed building wall to a height equal to the separation

distance, commencing at the height of the roof of the exposing building. In Appendix A, it is explained that "in the event of a moderate wind, flames can be expected to extend horizontally for as great a distance as they might otherwise extend upwards.

4.3.8.4 Where the roof of the exposing building has a fire resistance rating sufficient to contain the expected fire (based on the fire loading within the area), no exposure hazard is considered to exist throughout the roof.

4.3.8.5 Where the roof has a fire resistance rating less than necessary to contain an expected fire, means of protection should be provided in accordance with Table 4.3.8.2, taking into consideration the fire stability of the roof assembly involved, the fuel it could contribute, including roof insulation and covering, and its tendency to inhibit flaming through the roof.

4.3.8.6 Subject to 4.3.8.4 and 4.3.8.5, the number of stories expected to contribute to flaming through the roof should be considered to be the top story together with those stories that are successively located beneath the top story and are not separated from it, as indicated in 4.3.3.

4.3.8.7 High attic spaces should be counted as a story and be subject to 4.3.8.4 and 4.3.8.5. Where the height of the attic is low, interpolation between the values provided in Table 4.3.8.2 (Table 8) should be made.

Table 8. NFPA 80A requirements for minimum separation distance for exposing buildings with combustible/non-rated roof assemblies (NFPA, 2017, Table 4.3.8.2).

Number of storeys likely to contribute to flaming through the roof	Horizontal separation distance or height of protection above exposing fire (m)
1	7.5
2	10
3	12.5
4	15

NFPA 80A Annex A Explanatory Material section A.4.3.8 discusses the above requirements for protection from buildings of lower height. It is based on estimates of flame heights from a search of thousands of photographs, of which 176 showed flames above roofs at maximum or near-maximum heights (NFPA, 2014). It was indicated that the principal relationship was the number of storeys involved in the fire, and there was no discernible impact of the occupancy on flame height. NFPA 80A Table A.4.3.8 (Table 9) lists the average flame heights found as a function of storeys burning.

Table 9. NFPA 80A requirements for average heights of flames penetrating roofs (NFPA, 2017, Table A.4.3.8).

Number of storeys burning	Flame height above roof (storeys)
1	1.4
2	1.8
3	2.2
4	2.6
5	2.9
6	3.1

NFPA 80A notes that these values are lower than suggested by other British and Japanese work. Also, it is noted that these recommendations are not intended to provide adequate protection under unusual circumstances such as the heavy involvement of liquid fuels.

2.3.2 BRE *External fire spread: building separation and boundary distances*

BRE document BR 187 (Chitty, 2014) provides general recommendations for design to prevent external fire spread, although it does not specifically address fire spread from lower roofs. Key factors are summarised as follows:

- The extent of a fire in a building should be limited by compartmentation.
- Unprotected areas on a burning building are taken to fail immediately.
- Unprotected areas on an exposed building fail when the fire in the adjacent building reaches its peak intensity.
- Thermal radiation from a burning building is based on:
    - Total unprotected area on the elevation of a compartment
    - Compartment temperature which is dependent on fire load (purpose group), ventilation, insulation, and presence of a suppression system.
- Limiting the radiation intensity on an exposed building to 12.6 kW/m² unless:
    - The exposed building has a sprinkler system to control internal fire spread
    - The two buildings are of dissimilar size – a fire engineering analysis should be performed.

The design objectives are:

- to prevent fire spread to external combustible material on the exposed building occurring less than 10 min after the original fire reaches its peak
- to prevent ignition of the interior of an exposed building until 20 min after the original fire reaches its peak.

The 10-minute criterion was based on an increased probability of ignition of timber cladding or wooden window frames if receiving a heat flux of 12.6 kW/m² for more than 10 minutes. The 20-minute criterion was based on reduced-scale experiments done by Simms, Law and Wraight (1955) where a radiant panel was used to represent heat flux of 9 kW/m² at an external window covering 100% of the area of one wall. The window was assumed to have instantly broken and completely fallen out. Ignition of representative wood and fibre insulating board furniture was achieved after 24 minutes. Chitty noted that glass fallout is difficult to predict but quoted uncited experimental studies where cracking was achieved within 2 minutes when exposed to radiation of approximately 9 kW/m² and within 5 minutes when exposed to radiation of 5 kW/m².

2.3.3 Determination 94/003

Determinations by the New Zealand building regulator are publicly available and provide guidance "on matters of doubt or dispute to do with building work" (MBIE, 2019). Determination 1994/003 discussed roof-to-roof fire spread between adjacent unit titles (BIA, 1994). While this was a different mechanism than the roof-to-higher-wall mechanism covered in this research, the determination provides some relevant commentary on flame heights from roofs. The opinion of the BIA at the time was that:

> In the case of a roof, the flame front will emerge vertically. It can extend 10 or 20 metres, or even higher above the roof, so that depending on the length of the opening along the roof, the vertical radiating surface can be quite extensive. (BIA, 1994, p. 2)

In comparing flames from wall openings to flames from roofs:

> By contrast, in the case of a wall a flame emerging from an opening will turn vertically upwards, and will project only 1 or 2 metres horizontally from the opening. The area of flame on each side of an opening which can radiate to a neighbouring wall in the same plane as the wall on fire will generally be much smaller than for roof flames. The equivalent in the roof case would be a flame projecting only 1 or 2 metres above the roof, which experience indicates is rarely the case. (BIA, 1994, p. 2)

2.4 Discussion of building regulation requirements

2.4.1 Performance requirement comparison

The qualitative performance requirements are similar within the jurisdictions reviewed. The primary difference is in the level of quantitative prescription. They all suggest that fire spread shall be limited to prevent risk to life or other property. The UK has the only qualitative performance criteria that specifically mentions fire spread involving roofs. The US, UK and Canada do not provide quantitative requirements within the performance criteria or objectives. New Zealand and Australia provide quantitative heat flux criteria within either the NZBC (New Zealand) or Verification Method (Australia). The Australian maximum permissible external heat flux is much higher. As a comparison, in New Zealand, the boundary radiation must be limited to 30 kW/m² whereas the Australian Verification Methods CV1 and CV2 allow 80 kW/m². However, buildings on the boundary must also withstand this level of heat flux without ignition. At a distance of 1 m from the boundary, the NZBC allows a maximum of 16 kW/m² while the Australian Verification Method CV1 allows a maximum of 40 kW/m². The NZBC does not restrict the minimum critical ignition heat flux for external wall materials beyond 1 m from the boundary while the Australian Verification Methods require minimum critical ignition heat fluxes up to 6 m from the boundary.

2.4.2 Specific prescriptive requirement comparison

The New Zealand requirements for fire spread from lower roofs relate to the scenario of a compartment fire below the lower roof breaching the roof and potentially spreading fire to an adjacent exterior wall. There are fire-resistance tests for exterior ignition and penetration into a building such as NFPA 276 (NFPA, 2019) and BS 476-3:2004 *Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs*, which are required in other jurisdictions such as the US, Canada and the UK. However, the requirements of AS 1530.4:2014 *Methods for fire tests on building materials, components and structures – Fire-resistance tests for elements of construction* and NZS/BS 476-21:1987 *Fire tests on building materials and structures – Methods for determination of the fire resistance of loadbearing elements of construction* only look at fire exposures to the underside of roofs. There are no requirements in the current New Zealand building regulations to consider fire spread to a roof from external sources.

It appears that the origin of the current New Zealand requirements was in draft standard DZ 4226:1984, based on information from NFPA 80A. This is contrary to the statement in the 1992 Acceptable Solutions, which indicates that the external wall and roof requirements came from UK regulations. However, the UK regulations only included assembly buildings more than 1 storey, and the requirement was for reaction to fire (and unprotected openings in 1985). The original 1992 Acceptable Solution requirements are similar to what is included in the present versions, although drenchers have been removed as an option for the higher wall and the wording has changed slightly due to the separation of the Acceptable Solutions by occupancy type. Previously, NZS 1900 Chapter 5 had a related requirement but was limited to podium roof areas only.

Canada has similar distance requirements to New Zealand for situations where an external wall is next to a lower roof, but the requirements are limited to the presence of openings (windows and skylights) rather than requiring fire-resistant construction. The Canadian requirements also only apply to the case of the wall and roof being in the same building. The US IBC requirements require smaller distances and also less fire protection. Openings are allowed as long as they have protectives with a ¾ hour rating. Concessions for sprinklers below the roof are not included in the US or Canada.

Australia and Sweden have similar requirements to New Zealand although the distances are different. Compared to New Zealand, Sweden's requirements are nearly reversed (5 m of the external wall rated and 8 m of the roof) while Australia's are reduced (6 m of the external wall and 3 m of the roof). Concessions for sprinklers below the roof are included in Sweden and Australia, although in Australia, the roof covering must be non-combustible.

The NFPA 80A guideline, while not a regulatory requirement, provides more stringent guidance than the New Zealand prescriptive requirements, with up to 15 m horizontal and vertical separation required. These requirements vary based on the number of storeys potentially involved.

2.4.3 General external fire spread prescriptive requirements comparison

While New Zealand has arguably the most stringent prescriptive requirements for specific situations involving fire spread from beneath lower roofs to external walls, there are cases where the general roof and external wall requirements in other jurisdictions would exceed the New Zealand requirements, particularly where two separate buildings are involved and a boundary applies.

Residential buildings in Australia greater than 3 storeys built to the Acceptable Solution require the entire roof to be fire rated to 90/60/30 and loadbearing external walls must have 30 minutes of integrity up to 18 m away from a fire-source feature. Exceptions to the roof requirements are allowed if the covering is non-combustible. External walls for residential buildings greater than 2 storeys (Type A or B construction) must also be non-combustible. Australia also has fewer concessions for unprotected areas in fire-resisting external walls compared to New Zealand.

Canada and the US have more stringent requirements for unprotected areas close to another fire compartment or boundary when compared to New Zealand. The US IBC does not allow unprotected areas within a 3 ft (0.9 m) fire separation distance, and this is extended to 5 ft (1.5m) if the building is unsprinklered. Cladding is required to be non-combustible if up to 50% of unprotected openings are permitted in Canada, with a 3–7 m limiting distance depending on the area of the exposing building face. The maximum permitted size of a single unprotected area in an external wall is smaller for equivalent separations in Canada when compared with New Zealand.

Canada, the UK and the US also add external roof fire spread requirements, which are not required in New Zealand. The UK and Australia have limitations on the locations of rooflights relative to boundaries or, in the case of Australia, higher construction.

2.4.4 Fire resistance and reaction to fire requirements

There are generally two types of requirements for preventing external fire spread: fire resistance requirements and reaction-to-fire requirements. As discussed earlier in the section, jurisdictions include both types of requirements for fire spread from lower roofs in certain circumstances. Fire resistance requirements are intended to limit the heat exposure of potentially ignitable objects, either on the exterior of the building or inside unprotected areas such as windows, and the spread of fire products beyond the rated building element. Fire resistance does not prevent fire from igniting or spreading on the surface of a building element – for example, on an external wall. Reaction-to-fire requirements cover the surface fire spread aspect and limit how materials will respond to the heat exposure.

Fire resistance requirements for preventing horizontal fire spread are typically used to reduce the expected radiating area of a building on fire and, for the adjacent buildings, to limit the unprotected areas where fire can spread inside the building. The maximum radiating heat flux from a building on fire is estimated using the Stefan-Boltzmann law:

$$q''_{max} = \varepsilon\sigma T^4 \qquad \textbf{Eq. 2-1}$$

Where: q''_{max} is the maximum radiating heat flux (W/m²)

ε is the emissivity (how efficiently a surface can radiate)

σ is the Stefan-Boltzmann constant (5.67×10^{-11} kW/(m^2K^4))

T is temperature (K)

For calculating external fire exposures, emissivity is typically assumed to be 1 for fires in compartments. Temperatures used vary by literary source and expected fire conditions but a typical range is from 800°C (75 kW/m²) to 1100°C (200 kW/m²).

C/VM2 uses the following values as the design fire conditions for design scenario 4.5:

a. 83 kW/m² for FLED ≤ 400 MJ/m²
b. 103 kW/m² for 400 MJ/m² ≤ FLED ≤ 800 MJ/m²
c. 144 kW/m² for FLED ≥ 800 MJ/m²
d. 58 kW/m² for sprinklered firecells not containing storage occupancies or a storage occupancy with a capability to store to more than 3.0 m.

As a comparison, INSTA TS 950 (2014) nominates values of 84 kW/m² for residential, office, assembly and recreational occupancies and 168 kW/m² for shops, commercial, industrial, storage and other non-residential (reduced by 50% if sprinklered). Any unprotected areas in the external wall of the compartment on fire are expected to be radiating at the maximum value as per above. A configuration (or view) factor is then calculated to the nearest target on the adjacent building. The incident radiation on the adjacent building is compared to a threshold radiation where ignition could occur (reaction to fire). For vertical fire spread, fire resistance requirements are typically used to separate vertically adjacent unprotected areas or openings to prevent fire spreading between them. These could be vertical separations (spandrels) or horizontal projections from the building (aprons).

Allowable external wall thermal conditions

The parameter used for potential for ignition (reaction to fire) is typically heat flux. For horizontal fire spread C/VM2 does not restrict any external wall materials beyond 1.0 m across the relevant boundary and specifies a maximum received radiation heat flux of 16 kW/m² (MBIE, 2014b). It is noted that some materials may ignite below 16 kW/m², but Fire and Emergency intervention is anticipated. Any external wall materials within 1 m of a boundary are required to either be non-combustible or withstand 30 kW/m² radiant heat flux for 30 minutes (importance level 3 and 4 buildings) or 15 minutes (importance level 1 and 2 buildings).

Other sources provide other guidance on allowable incident heat flux levels. Examples are listed in Table 10. Collier (1996) notes that "fire windows differ from ordinary windows by remaining intact and are assumed to reduce the transmitted radiation by 50%". Subsequent work by Cowles (1997) found a maximum radiation attenuation of 45% for Georgian wired glass, with ceramic, heat-strengthened borosilicate and toughened fire-resistant calcium silica float glass each on the order of 25–30%.

Table 10. Sources of maximum allowable incident heat flux for external walls.

Source	Description	Allowable heat flux (kW/m²)
MBIE, 2014b	C/VM2 Verification Method	16
Collier, 1996	Exterior insulation and finish systems (EIFS)	9.0
Collier, 1996	Timber	12.5
Collier, 1996	Fibre-cement board	25.0
Collier, 1996	Contents behind non-fire-rated glazing	25.0
Collier, 1996	Contents behind fire-rated glazing	50.0
NFPA, 2017	Typical cellulosic façade material	12.5
Burrell & Hare, 2006	Soft woods	12.6
Burrell & Hare, 2006	Plastic and composite skinned materials	10

Comparing incident heat flux or energy on a surface to a fire resistance rating is not as straightforward as the allowable heat flux values for reaction to fire. One method that might be considered is Nyman's method (2002) that calculates a total energy dose by integrating the emissive power of fire gases during a standard fire test. The estimated incident radiant heat flux on a building element in a fire test using the ISO 834 temperature curve is shown in Figure 14, using the Stefan-Boltzmann equation and assuming an emissivity of 1.

Using Nyman's time equivalency method of integrating the incident radiant heat flux to determine an overall heat input to the building element, a comparative time equivalence can be determined for a constant heat flux at typical allowable heat flux levels for walls as shown in Figure 15. For example, it would take about 300 minutes of exposure to 16 kW/m² heat flux for a wall to receive the equivalent total energy from 60 minutes in a standard fire resistance test using the ISO 834 temperature curve. This is for illustration purposes only because it is unknown how well Nyman's method would work at relatively low constant heat flux levels. However, it would be expected that building elements would perform substantially longer at lower incident heat flux levels when compared to the conditions in a standard fire resistance test.

Another difference between applying the concept of fire resistance rating to an external building element compared to internal elements is that standard fire tests such as AS 1530.4:2014 include a pressure requirement on the order of 20 Pa. This pressure is similar to the overpressure that might be present at the top of a compartment in post-flashover conditions. Fires external to the building would not create such pressure because there is no confinement of the fire products. However, wind pressure could create substantially higher pressure differentials (Shelton, 2009).

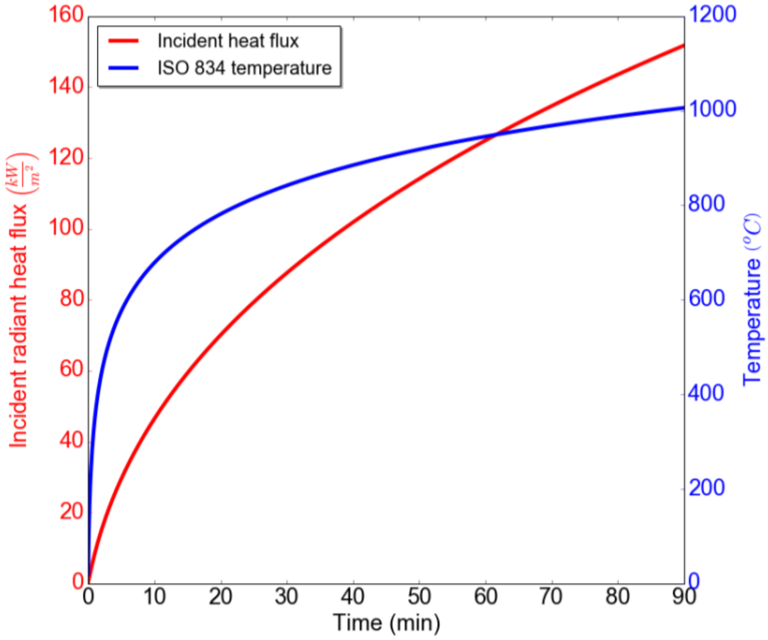


Figure 14. Gas temperature and estimated incident radiant heat flux on a building element during a fire test using the ISO 834 time-temperature curve.

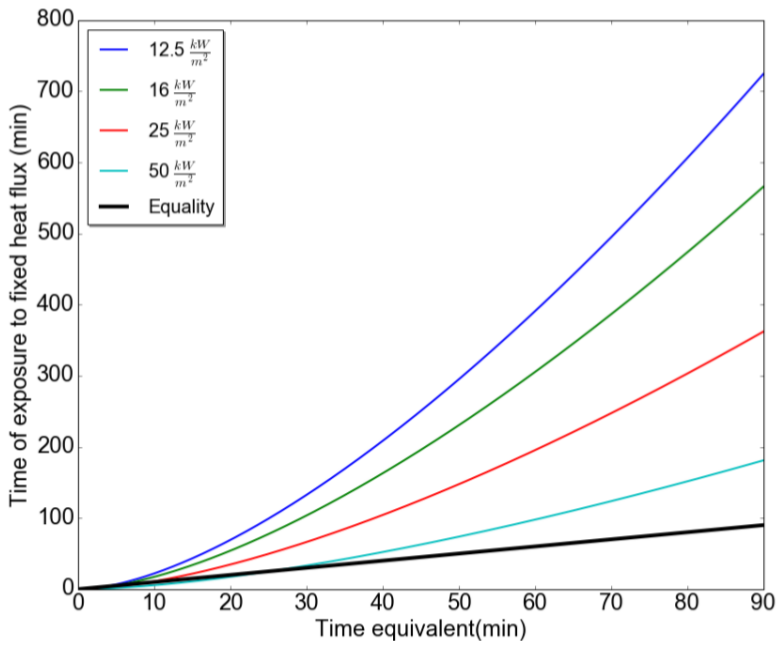


Figure 15. Time equivalence using Nyman's method assuming constant heat flux input at typical allowable heat flux levels for external walls.

2.5 Regulatory and guidance document conclusions

Section 2 has provided an overview of the current regulatory requirements and guidance documents that provide information on how fire spread from lower roofs should be managed in New Zealand, Australia, Canada, the UK and the US. A comparison can be made of the specific fire spread from lower roofs requirements in each jurisdiction. However, the risk of this fire spread mechanism is also partially managed with general external building fire spread requirements, and these are situationally dependent (building occupancy and/or construction dependent) in most of the jurisdictions, so a simple comparison is difficult. Also, there is limited guidance on how the prescriptive requirements relate to the overall performance objectives.

Section 3 investigates approaches to estimate the thermal impact of fires from lower roofs on adjacent higher external walls.

3. Fire research literature review

While no specific methodology has been found for evaluating the thermal impact of the fire spread from lower roofs design fire described in C/VM2, there is a substantial body of research that may be applicable to this situation. Work has been done to characterise the exposure of external walls to radiation from nearby unprotected wall areas or openings in adjacent buildings. Models have also been developed to estimate heat flux from fire sources such as large pool fires on their surroundings. This section describes potentially useful concepts and models from existing fire science literature and discusses possible uses for evaluating fire spread from lower roofs.

3.1 Radiation models

Several models are available for predicting flame radiation incident on targets. Beyler (2016) discusses a number of radiation models that have been applied to fire engineering and the most relevant are summarised here.

3.1.1 Point source model

The point source model is a simple correlation that has been widely used and has been found to be relatively accurate compared to other correlations for modelling heat flux on targets near fires in compartments (Fleury, 2010). The point source model as described by Croce and Mudan (1986) assumes the fire to be a spherical radiator radiating heat uniformly in all directions. The incident radiative heat flux $\dot{q}''$ (in kW/m²) to a target at a radial distance R (in m) and with a normal at angle θ to the line of sight from the target is given by:

$$\dot{q}'' = \frac{\dot{Q}_r cos\theta}{4\pi R^2} \qquad \textbf{Eq. 3-1}$$

Where $\dot{Q}_r$ is the total radiative energy output of the fire in kW. The location of the equivalent point source is at the centre of the fire and at half of the flame height as shown in Figure 16.

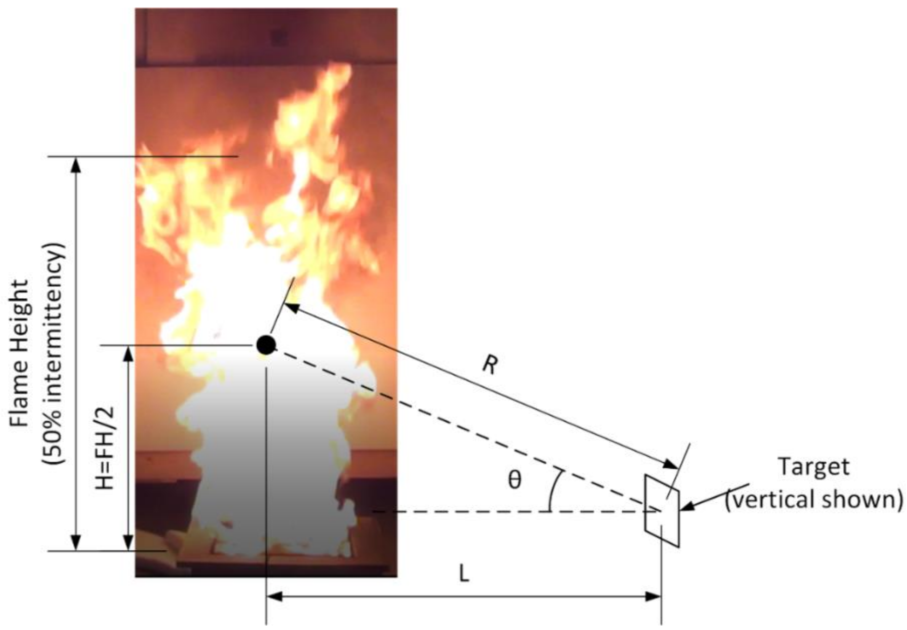


Figure 16. Point source model geometry.

The radiative energy output is calculated as a fraction of the total heat release rate $\dot{Q}_r = \chi\dot{Q}$ where χ is the radiative fraction and is typically near 0.3 for most fire conditions but can range from 0.1 to 0.6 (Croce & Mudan, 1986).

For a vertical target such as that shown in Figure 16, the equation can be rewritten by substituting $\dot{Q}_r$ and $cos\theta$ in terms of L and R:

$$\dot{q}'' = \frac{L}{4\pi R^3}\chi\dot{Q} \quad \textbf{Eq. 3-2}$$

The peak value ($\dot{q}''_{max}$) will occur at θ= 0 ($L = R$):

$$\dot{q}''_{max} = \frac{\chi\dot{Q}}{4\pi R^2} \quad \textbf{Eq. 3-3}$$

Further substitution of R in terms of L and H results in the following form:

$$\dot{q}'' = \frac{L}{4\pi(H^2 + L^2)^{\frac{3}{2}}}\chi\dot{Q} \quad \textbf{Eq. 3-4}$$

3.1.2 Vertical cylinder model

Mudan (1987) and Shokri and Beyler (1989) proposed a detailed method assuming the flame has cylindrical geometry. This method assumes the radiative heat flux is the product of the effective emissive power of the flame E (kW/m²) and a configuration factor F_{12} based on the distance to the target and the flame geometry:

$$\dot{q}'' = EF_{12} \quad \textbf{Eq. 3-5}$$

The effective emissive power for hydrocarbon pool fires is calculated from the pool diameter D (m) as follows:

$$E = 58(10^{-0.00823\,D}) \quad \textbf{Eq. 3-6}$$

For fire spread from lower roofs, the configuration factor to a vertical ($F_{12,V}$) target applies:

$$F_{12,V} = \frac{1}{\pi S}tan^{-1}\left(\frac{h}{\sqrt{S^2-1}}\right) - \frac{h}{\pi S}tan^{-1}\sqrt{\frac{S-1}{S+1}} + \frac{Ah}{\pi S\sqrt{A^2-1}}tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \quad \textbf{Eq. 3-7}$$

The parameters *S*, *h*, *A* and *B* can be calculated as follows:

$$S = \frac{2L}{D} \quad \textbf{Eq. 3-8}$$

$$h = \frac{2H}{D} \quad \textbf{Eq. 3-9}$$

$$A = \frac{h^2 + S^2 + 1}{2S} \quad \textbf{Eq. 3-10}$$

$$B = \frac{1 + S^2}{2S} \quad \textbf{Eq. 3-11}$$

The relevant geometry is shown in Figure 17.

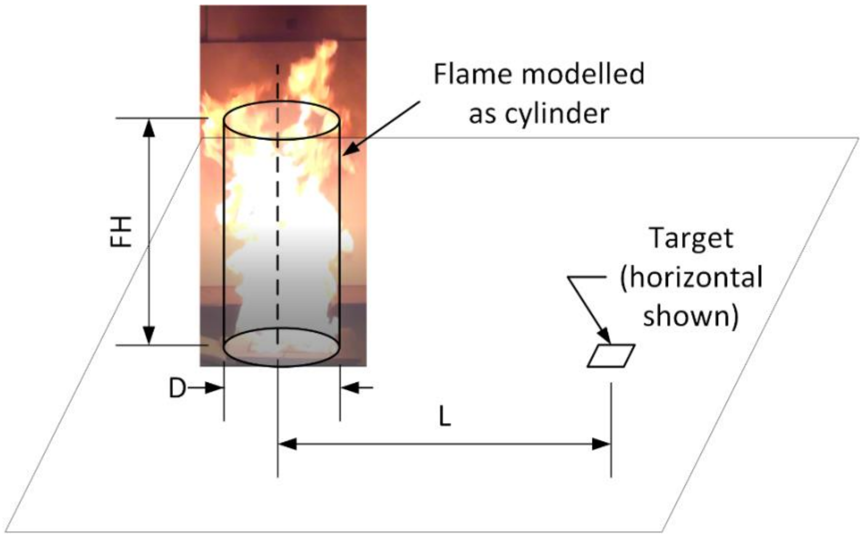


Figure 17. Vertical cylinder flame radiation model geometry.

Non-circular fires with an area aspect ratio close to 1 can be approximated with an equivalent fire diameter D calculated by solving $\frac{\pi D^2}{4} = non - circular\ fire\ area$ (and $R = D/2$). The configuration factors can be combined using superposition to find the view factor at different vertical positions relative to the cylinder. Above the tip of the flame, a view factor to the top disk surface is added (Hottel, 1931):

$$F_{disk} = \frac{H}{2}\left[\frac{Z}{(Z^2 - R^2)^{\frac{1}{2}}} - 1\right] \quad \textbf{Eq. 3-12}$$

The parameters H, R and Z are calculated as follows:

$$H = \frac{FH}{L} \quad \textbf{Eq. 3-13}$$

$$R = \frac{D}{2L} \quad \textbf{Eq. 3-14}$$

$$Z = 1 + R^2 + H^2 \quad \textbf{Eq. 3-15}$$

3.1.3 Tilted cylinder model

Mudan (1987) extended the cylindrical flame radiation model to the case where the cylinder is tilted, which can represent a flame under wind conditions. Equation 3-7 then becomes:

$$\begin{aligned}\pi F_V = {} & \frac{acos\theta}{b - asin\theta}\frac{\left(a^2 + (b+1)^2 - 2b(1 + asin\theta)\right)}{\sqrt{AB}}\tan^{-1}\sqrt{\frac{A}{B}}\left(\frac{b-1}{b+1}\right)^{\frac{1}{2}} \\ & + \frac{cos\theta}{\sqrt{C}}\left[\tan^{-1}\frac{ab - (b^2-1)sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\frac{\sqrt{(b^2-1)}sin\theta}{\sqrt{C}}\right] \\ & - \frac{acos\theta}{b - asin\theta}\tan^{-1}\sqrt{(\frac{b-1}{b+1})}\end{aligned} \quad \textbf{Eq. 3-16}$$

The parameters a, b, A, B and C are as follows:

$$a = \frac{FH}{R}, R = \frac{D}{2} \quad \textbf{Eq. 3-17}$$

$$b = \frac{L}{R} \quad \textbf{Eq. 3-18}$$

$$A = a^2 + (b+1)^2 - 2a(b+1)sin\theta \quad \textbf{Eq. 3-19}$$

$$B = a^2 + (b-1)^2 - 2a(b-1)sin\theta \quad \textbf{Eq. 3-20}$$

$$C = 1 + (b^2 - 1)\cos^2\theta \quad \textbf{Eq. 3-21}$$

Where θ is the angle between the cylinder axis and vertical, as shown in Figure 18. As with the vertical cylinder, a view factor to the top disk surface is added for heights above the flame tip.

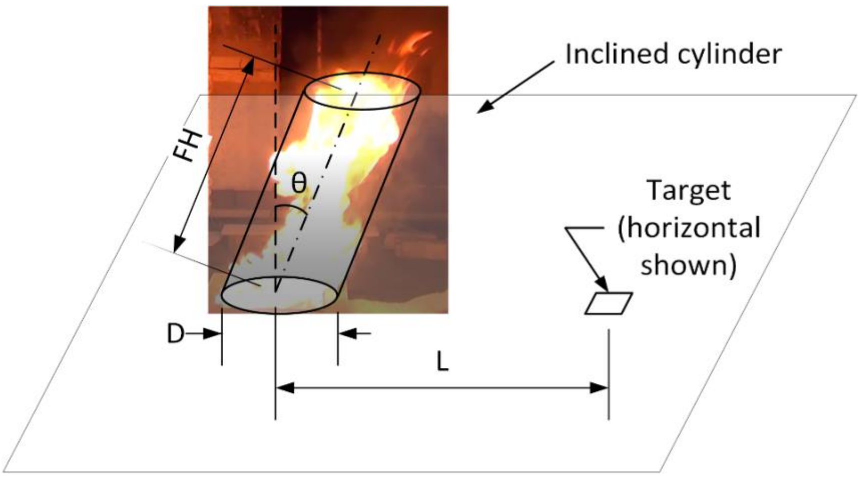


Figure 18. Geometric parameters for Mudan's tilted cylinder configuration factor model (Mudan, 1987).

3.1.4 NRL/HAI model

A collaboration between the Naval Research Laboratory (NRL) and Hughes Associates Inc (HAI) developed a model for estimating the amount of radiation from a square propane fire adjacent to a wall (Back, Beyler, Dinenno & Tatem, 1994). The fire heat release rate ranged from 50 kW to 500 kW with burner edge lengths from 0.28 m to 0.70 m. The maximum heat flux (on the wall closest to the vertical centreline of the fire plume) is only discussed here because that will be the worst case, although Back et al. did develop a lateral distribution for the heat flux at other positions horizontally along the wall. Three regions were identified, with the heat flux observed to be relatively constant from the base of the fire to 40% of the flame height, then linearly decreasing to 20 kW/m² at the tip of the flame and then decreasing proportional to the height above the flame to the -5/3 power. The peak heat flux $\dot{q}''_p$ (in kW/m²) was estimated using a simple mean beam length approach:

$$\dot{q}''_p = E(1 - e^{-k_a \dot{Q}^{1/3}}) \quad \textbf{Eq. 3-22}$$

Where E is the blackbody emissive flame power (200 kW/m²) and $k_a$represents the extinction coefficient (0.09 kW$_{-1/3}$) based on a curve fit of the experimental data from Back et al. (1994).

The linear equation for the heat flux on the wall nearest the centreline of the plume ($\dot{q}''_{CL}$) for the portion of the flame from 40% to 100% of the flame height was as follows:

$$\dot{q}''_{CL} = \dot{q}''_p - \frac{5}{3}\left(\frac{Z}{FH} - \frac{2}{5}\right)(\dot{q}''_p - 20) \qquad \textbf{Eq. 3-23}$$

Above the tip of the flame, the equation for the centreline heat flux on the wall becomes:

$$\dot{q}''_{CL} = 20\left(\frac{Z}{FH}\right)^{-\frac{5}{3}} \qquad \textbf{Eq. 3-24}$$

In Eq. 3-20 and 3-21, Z is the height above the base of the flame.

3.1.5 Radiation model summary and discussion

Options for calculating the radiative heat flux to a higher wall at a distance to a lower roof on fire include the point source, vertical cylinder and tilted cylinder model. These models are all based on radiative heat transfer to the wall only. This assumption becomes less valid as the air temperature at the wall and therefore convection to the wall increases, which would be expected if the flames are in close proximity to the wall. Beyler (2016) cautions the use of the point source model at heat fluxes above 5 kW/m² (or at separation distances less than 2.5 times the fire diameter) although Fleury (2010) found that the point source model worked relatively well up to 25 kW/m².

If the wall is directly adjacent to the fire, the NRL/HAI correlation is another option. This correlation has some basis in fundamental theory (i.e. the mean beam length formula) but otherwise is essentially a "best fit" to empirical data. This means that the use of this model outside of the empirical test parameters is questionable. It is based on propane fires, which are relatively quite small compared to fires that might be expected to penetrate roofs. A fire source within a building will typically involve different fuels and may be influenced by ventilation flow paths and heat transfer within the structure below the roof. A comparison of the predictions that these approaches give for a range of scenarios is included in section 6.3.

3.2 Flame height

3.2.1 Flame height correlations

The methods of determining radiation discussed previously require estimates of heat release rate and flame height. There are no known sources of measured heat release rates of fires that have vented through the roof of actual buildings in real fires. However, as discussed in section 2.4.1, Pingree (1968), referenced in NFPA 80A, gives estimates of maximum flame heights from roof-penetrating flames. A number of researchers have developed correlations for flame heights in free-burning fires (Heskestad, 2016). Heskestad (1984) himself has developed a widely used and validated correlation for flame height, FH. The form of Heskestad's correlation for most combustibles present in residential or commercial buildings under normal atmospheric conditions is as follows:

$$FH = -1.02D + 0.235\dot{Q}^{2/5} \qquad \textbf{Eq. 3-25}$$

Where D is the equivalent fire diameter in m and $\dot{Q}$ is the total heat release rate in kW. While the correlation was originally developed using empirical pool fire data, it has also been shown to work on in-depth fires (Heskestad, 1997) in tall combustibles. Heskestad's correlation produces the mean flame height as opposed to the maximum flame height. The mean flame height is based on the height where the flame is 50% intermittent, i.e. the height where 50% of the time the tip of the flame is above and 50% below.

It is unclear what intermittency Pingree's (1968) data might be based on, and in fact the smoke produced in real building fires may obscure the tip of the flame, particularly when close to maximum values. There is also uncertainty in how a fire source that consists of a compartment with a roof opening would relate to a typical free-burning fuel package. However, the flame height data from Pingree can be used with different roof opening geometries to estimate the heat release rate as a first attempt. Ingason and Lönnermark (2011, 2014) used a similar approach for industrial buildings. They found a slightly different correlation using a 1:10th scale model in a calorimeter:

$$L = -0.38D + 0.219\dot{Q}^{2/5} \qquad \textbf{Eq. 3-26}$$

They also found that, for wide aspect ratio fires, a slightly better correlation was found using the shorter side of the fire base W:

$$L = -0.5W + 0.21\dot{Q}^{2/5} \qquad \textbf{Eq. 3-27}$$

3.2.2 Flame tilt

Studies done on the lengthening effect of flames in wind conditions have found minimal differences up to flame deflection angles of 60°, with up to 30% longer flames at higher deflection angles (Heskestad, 2016). There are a number of correlations that have a similar form:

$$cos\theta = \begin{matrix} du^{*e}\ for\ u^* \geq 1 \\ 1\ \ for\ u^* < 1 \end{matrix} \qquad \textbf{Eq. 3-28}$$

Where θ is the flame tilt angle, u^* is the non-dimensional velocity and d and e are empirically determined constants that vary depending on the source. Heskestad (2016) includes a plot comparing four available correlations, which shows a substantial amount of scatter, and notes that the American Gas Association (AGA) coefficients d = 1 and e = -0.5 (based on data from liquefied natural gas pools) provide the best overall fit.

The relationship between the non-dimensional velocity and flame tilt angle is shown in Figure 19. The non-dimensional velocity u^* is calculated as follows:

$$u^* = \frac{u_w}{\left(\frac{g\dot{m}''_\infty D}{\rho_a}\right)^{\frac{1}{3}}} \qquad \textbf{Eq. 3-29}$$

Where $u_w$is the wind velocity in m/s, g is the acceleration due to gravity (9.81 m/s2), $\dot{m}''_\infty$ is the mass burning rate per unit pool area (note that this correlation was developed using pool fires), D is the pool diameter, and ρ_a is the ambient density (kg/m³).

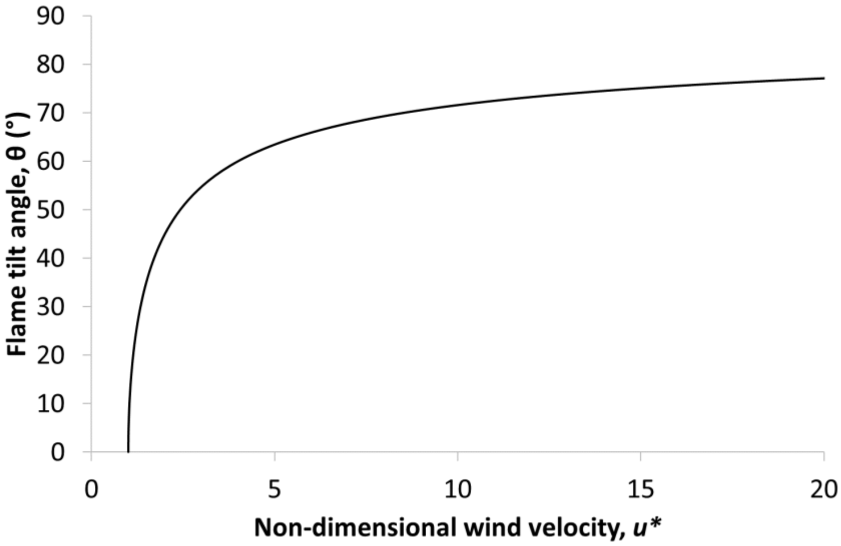


Figure 19. Flame tilt angle versus non-dimensional wind velocity u^* using the AGA correlation.

3.3 Conclusions

This section has investigated potential fire engineering approaches to evaluate the thermal impact of flames from lower roofs on higher adjacent walls. Three options for calculating the heat flux and one option each for flame height and flame tilt were described. However, no specific basis for validating these approaches for fire spread from lower roofs was identified in the literature. Section 4 describes a series of reduced-scale open-air and compartment experiments that provide an initial basis for validation.

4. Experimental study

A series of open-air and reduced-scale compartment experiments were conducted that investigated the impact on the flame height, heat flux, gas temperature and HRR from varying a range of different experimental parameters, including:

- fuel type
- proximity of burning fuel to vertical wall
- surface area of fuel
- location of burning fuel in compartment
- location of horizontal opening in compartment ceiling relative to location of burning fuel.

The purpose of the experimental study was to compare experimental measurements for flames projecting from an opening in a lower roof with predictions from existing correlations. This in turn would enable an engineering design method for estimating both flame height and heat flux on walls above a lower roof to be developed.

4.1 Experimental programme

Four different series of experiments were conducted in the experimental programme:

- Series 1: Free-burn experiments – although not actually simulating flames projecting from a lower roof, a series of free-burn experiments with propane, heptane and wood cribs were conducted with different horizontal offset distances relative to a vertical wall surface.
- Series 2: Compartment experiments (no offset) – the edge of a 300 × 300 mm horizontal ceiling opening was located with no offset to the vertical wall above the opening on the exterior of the compartment.
- Series 3: Compartment experiments (300 mm offset) – the edge of the 300 × 300 mm horizontal ceiling opening was located 300 mm from the vertical external wall.
- Series 4: Compartment experiments (700 mm offset) – the edge of the 300 × 300 mm horizontal ceiling opening was located 700 mm from the vertical external wall.

All experiments were conducted under the BRANZ ISO 9705 exhaust hood, which was used to measure the heat release rate through oxygen depletion calorimetry.

4.2 Fuel types

Three different fuel types were used in the experiments: propane gas, heptane and wood cribs. In Series 1, all three fuel types were used, while in Series 2–4, only heptane and wood cribs were used.

4.2.1 Propane

The standard ignition source used in ISO 9705:1993 *Fire tests – Full-scale room test for surface products* was the propane gas burner for the Series 1 experiments. The burner has a 170 × 170 mm horizontal top surface area that is 300 mm above floor level. The gas flow rate was measured using a mass flow meter.

4.2.2 Heptane

Nominally, 3 L of heptane was used for the heptane experiments. The heptane was contained in either a 250 × 250 mm, 300 × 300 mm or 400 × 400 mm pan. The pan was located in a water bath to prevent warping while being heated by the flames. The sides of this retention pan were insulated using a ceramic fibre blanket to minimise heat transfer to the pan. To minimise the water evaporation contribution to the mass loss rate, the gap between two pans was covered by a tightly fitted calcium silicate board (see Figure 20(a)). For the compartment experiments (Series 2–4), the heptane/water pan set-up was seated on a fuel bed platform supported by a load cell (see Figure 20(b)), while for the free-burn experiments (Series 1), the heptane and water pans sat directly on a protective platen on top of the load cell.

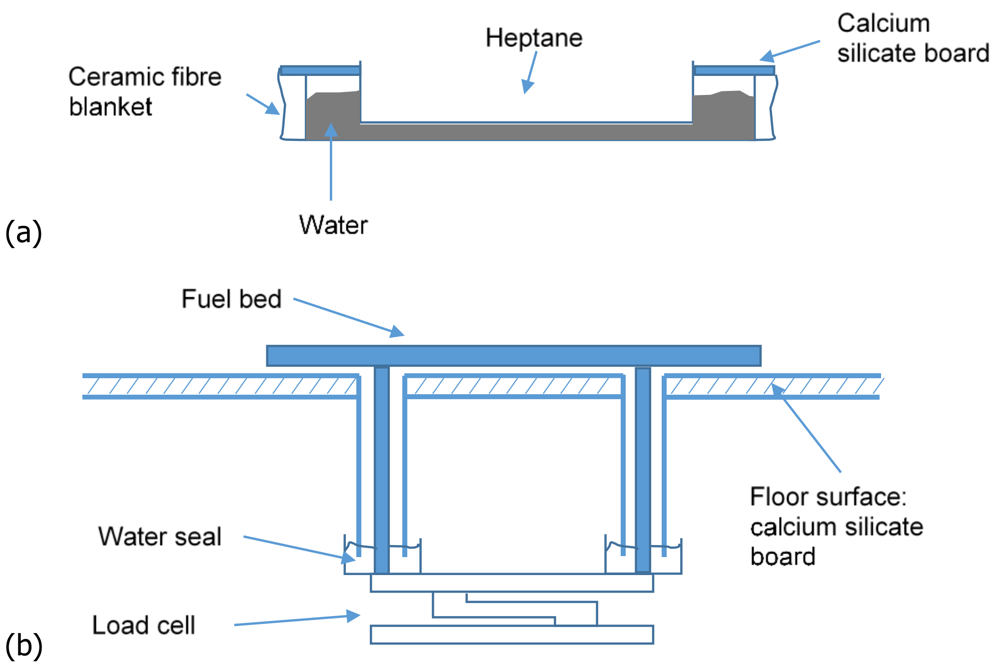


Figure 20. Heptane fuel pan set-up: (a) heptane pan and retention pan; (b) fuel bed.

4.2.3 Wood cribs

The wood cribs used in Series 1–4 consisted of nominally 22 × 22 mm cross-section × 340 mm long sticks of *Pinus radiata* in 13 alternating layers with nine sticks per layer and 18 mm horizontal clearance between sticks. The wood crib specifications are shown in Appendix B.

Prior to each test, the crib was conditioned to equilibrium under standard conditions of (50±5)% relative humidity and a temperature of (23±2)°C. Equilibrium was deemed to have been reached when the mass did not differ by more than 0.1% or 0.1 g, whichever was greater, over a 24-hour period.

4.3 Experimental measurements

4.3.1 Flame height measurements

Projected flame heights were calculated at 50% intermittency after processing still frames extracted from the experimental video every 0.5 s. A flame region was extracted from each image. The extracted images were overlapped over a 10 second period to identify the 50% intermittency region. Therefore, a single averaged flame height was obtained for every 10 seconds of experiment time.

For the Series 1 experiments, the flame height was taken from the top of the gas burner (for propane fuel), the top edge of the fuel pan (for heptane fuel) or the base of the wood crib. For the Series 2–4 experiments, the flame height was taken from the outer top surface of the compartment.

4.3.2 Incident heat flux measurements

Plate heat flux meters (pHFMs) were manufactured as shown in Figure 21 consisting of (from exposed side to unexposed side) a thin metal plate, two layers of ceramic fibre board and a calcium silicate board. The assembly was fastened together by two thin metal wires. The metal plate surface was sprayed with a black colour high-temperature paint such that the emissivity (and absorptivity) of the metal surface was assumed to be 0.9 (Veloo & Quintiere, 2013). To prevent abrasion of the calcium silicate board by the wire, a single layer of duct tape was applied to the back surface of the calcium silicate board. Details of the construction of the pHFMs and the calibration and the heat flux measurement correlations are included in Appendix A and Appendix B, respectively, of BRANZ Study Report SR360 (Frank et al., 2018).

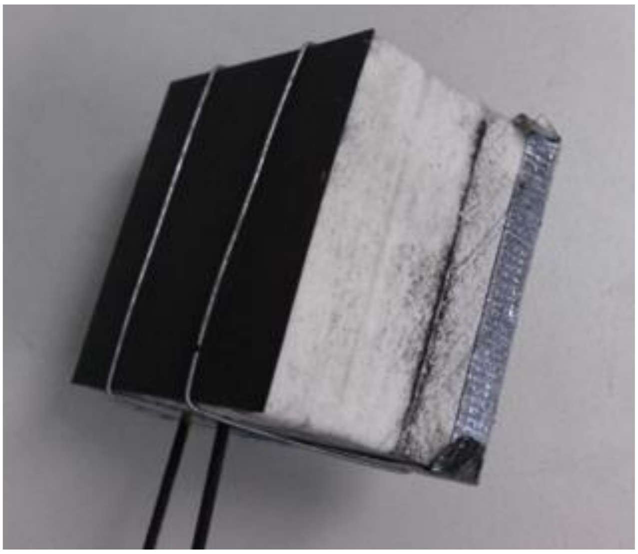


Figure 21. Plate heat flux meter.

In addition to the pHFMs, a number of commercial Schmidt-Boelter-type water-cooled heat flux meters (cHFMs) were used to measure both total heat flux and radiative flux.

All heat flux measurement devices were inserted into a vertical wall of 15 mm thick calcium silicate board such that the face of the device was flush with the exposed face of the wall panel.

4.4 Free-burn configuration and measurement locations

In the Series 1 experiments, the burning fuel was placed on the projected centreline of a vertical wall (constructed from 15 mm thick calcium silicate board) at the nominated offset distance (see section 4.6). A series of eight pHFMs were spaced at a nominal 300 mm centre-to-centre on the vertical centreline of the wall, and four cHFMs were also located between or beside some of the pHFMs – an elevation showing the layout of the different heat flux measuring devices is shown in Figure 22.

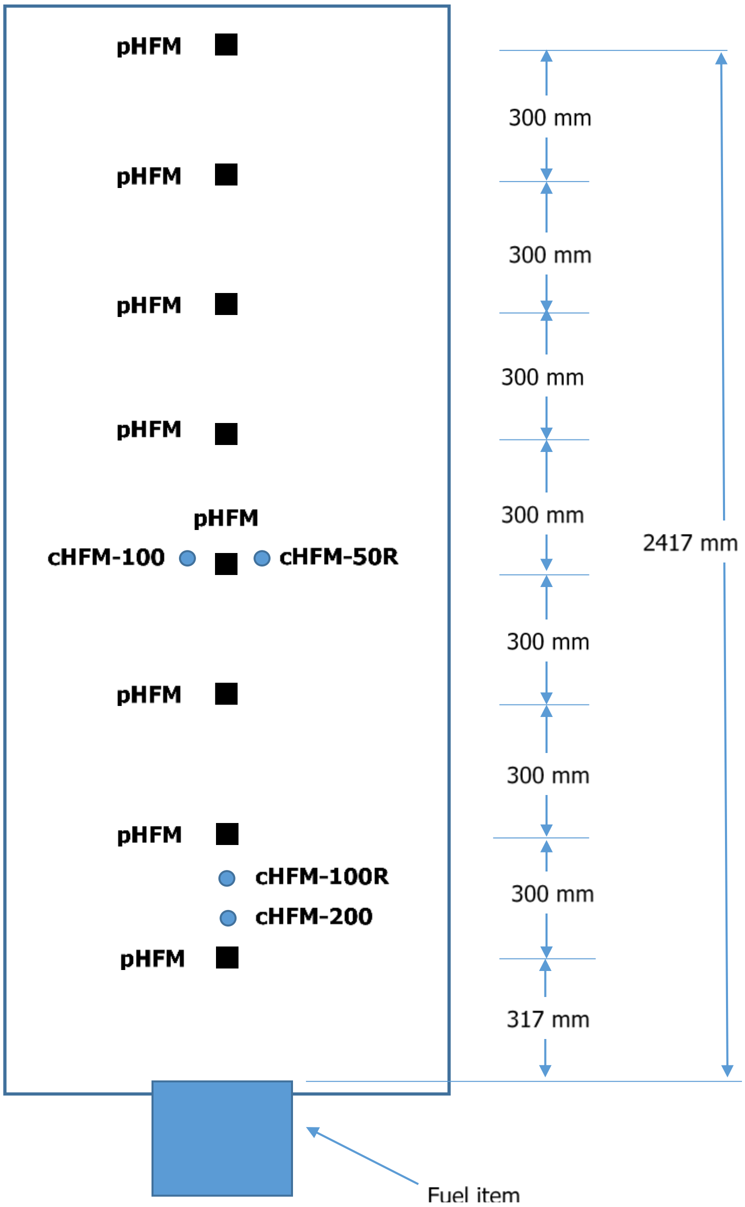


Figure 22. Elevation showing location of heat flux measuring devices.

In Figure 22, the code for each cHFM signifies its rating in kW/m2 as well as if it is a radiation-only gauge – for example, cHFM-200 is a 200 kW/m2 total cHFM, while cHFM-50R is a 50 kW/m2 radiation-only cHFM. The two cHFMs located between the lowest and second lowest pHFM are nominally 50 mm apart centre-to-centre about the midpoint between the two PHFMs. The two cHFMs beside the fourth pHFM from the bottom are nominally centred 50 mm each side of the vertical centreline and on the horizontal centreline of the pHFM. The radiation-only cHFM measurements were ultimately not used due to the inability to keep the window free of soot using an air purge during the experiments.

4.5 Compartment configuration

In the Series 2–4 experiments, the fires were located in a 1.3 m (D) × 1 m (W) × 0.8 m (H) internal dimension compartment. The compartment was made of 15 mm thick calcium silicate boards, and a layer of 12 mm thick ceramic fibre board was added as an internal lining material. Physical and thermal properties are shown in Table 11.

Table 11. Physical and thermal properties of compartment materials

	Calcium silicate board[1]	Ceramic fibre board[2]
Thickness	0.015 m	0.012 m
Density	975 kg/m^3	280 kg/m^3
Thermal conductivity	0.242 W/m-K	0.0002×T(K)-0.05 W/m-K
Heat capacity	-	1130 J/kg-K

Two fuel beds were located in the compartment to check the effect of the fuel location in the compartment on the heat release rate, projected flame heights and heat flux values, as shown in Figure 23.

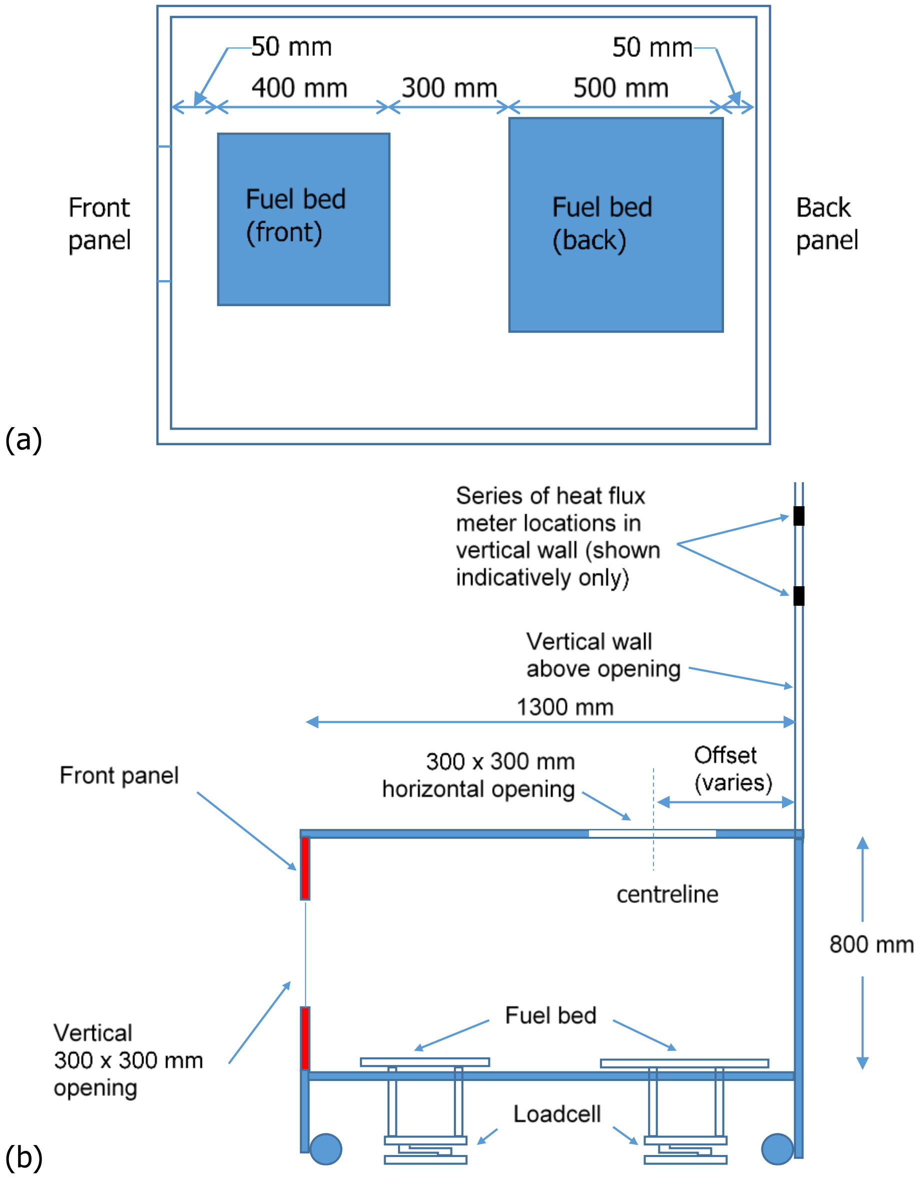


Figure 23. Compartment configuration: (a) plan view of fuel bed layout; (b) cross-section.

1 www.promat-ap.com/download/file/en/f4c8910657fd49ecb065a789008f381a?rev=9b977641-268d-4368-8f3b-48ee83df33dd
2 www.morganthermalceramics.com/media/4711/superwool-non-vf-boards.pdf

Each fuel bed was placed on a load cell (Avery Berkel T109 super-precision load cell, 30 kg) to measure fuel mass changes as shown in Figure 23(b). Mass loss rate data was recorded to measure vaporisation or pyrolysation and was also used to estimate heat release rates based on the heat of combustion established from free-burning fires (outside of a compartment), assuming complete combustion.

Figure 24 gives a schematic representation of the seven pHFMs and five cHFMs that were located in the vertical wall at the rear end of the compartment. The cHFMs were placed centrally between the pHFMs.

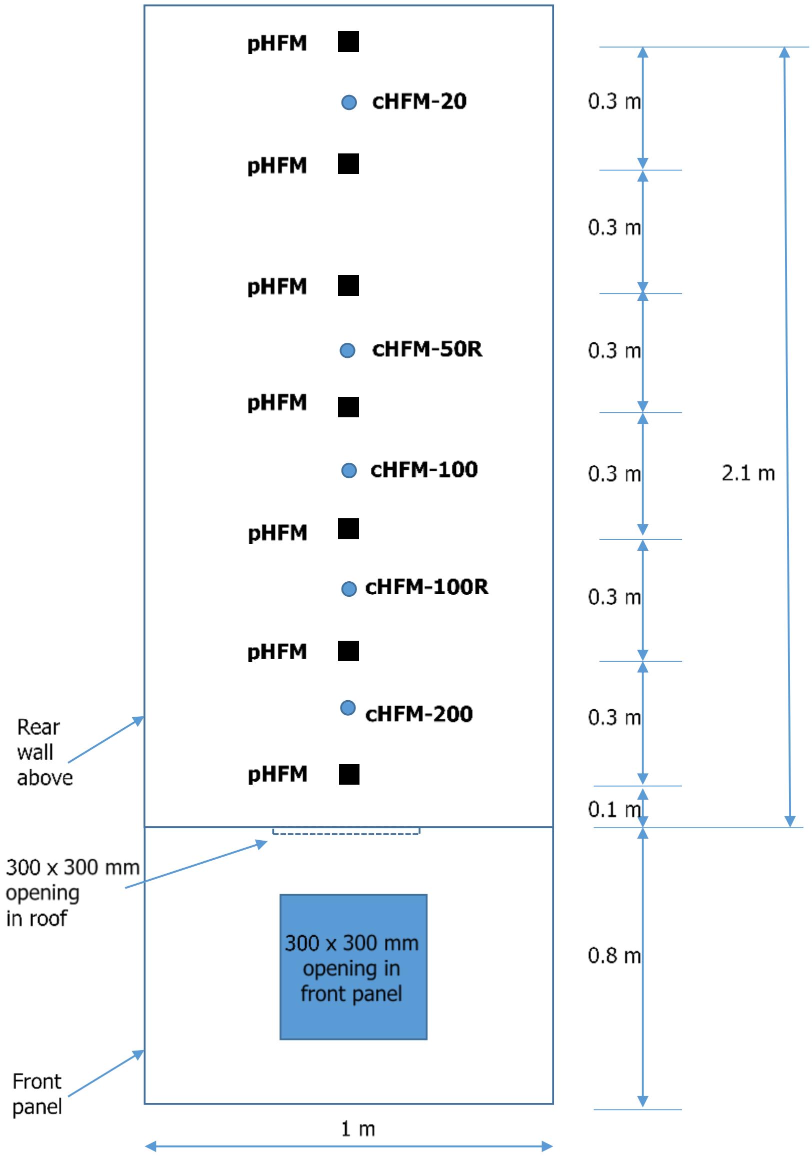


Figure 24. Elevation showing location of heat flux measuring devices.

Figure 24 also shows the relative location of the 300 × 300 mm vertical ventilation opening, which is centrally located in the front panel of the compartment, noting that the front panel is located horizontally 1300 mm from the rear vertical wall panel. The 300 × 300 mm horizontal opening in the ceiling of the compartment is also shown in cross-section. With reference to Figure 23(b), the offset of this horizontal opening is from the face of the vertical wall panel by varying amounts (150, 450 and 850 mm) during Series 2–4 experiments.

4.6 Test matrix

A summary of the details of the different configurations in the Series 1–4 experiments is given in Table 12. The ceiling opening offset and fuel location offset are all relative to the vertical wall panel with the pHFMs and cHFMs and are to the centre of the respective opening or fuel item (propane burner, fuel pan or wood crib). Results from the experiments are described in section 5.

Table 12. Test matrix for Series 1–4 experiments.

Series	Expt. ID	Fuel type	Pan size (mm × mm)	Compart./ free-burn (C/FB)	Ceiling opening offset (mm)	Fuel location offset (mm)
1	1A	Propane		Free-burn		85
	1B					500
	1C					1000
	1D					1500
	1E	Heptane	300 x 300			150
	1F		400 x 400			200
	1G	Wood				170
	1H					170
	1I					500
	1J					1000
2	2A	Heptane	300 x 300	Compart.	150	150
	2B		300 x 300			1050
	2C		250 x 250			150
	2D	Wood				150
	2E					150
	2F	Heptane	300 x 300			150
	2G		250 x 250			150
	2H		250 x 250			1050
3	3A	Heptane	300 x 300	Compart.	450	150
	3B		250 x 250			150
	3C	Wood				150
4	4A	Heptane	300 x 300	Compart.	850	150
	4B		250 x 250			1050
	4C	Wood				150

5. Experimental results

5.1 Propane free-burn experiments

In experiments 1A–1D (propane), the burner was progressively moved further away from the vertical wall, starting hard against the wall (170 mm horizontal offset to burner centre) up to a horizontal offset of 1500 mm (to the burner centre).

The orientation of the fire plume created by the propane burner tended to not be stable, and the angle to vertical varied during the experiments. This caused some fluctuation in measured flame height and heat flux when the plume angle changed.

In Figure 25, the graphs on the left-hand side of the figure show measured flame height and the corresponding prediction using Heskestad's correlation (Eq. 3-25) and the measured HRR using oxygen consumption calorimetry. The graphs on the right-hand side show the measured heat flux at the third pHFM, i.e. at 917 mm above the fuel item and compare these experimental measurements to the predictive models described in section 3.1.

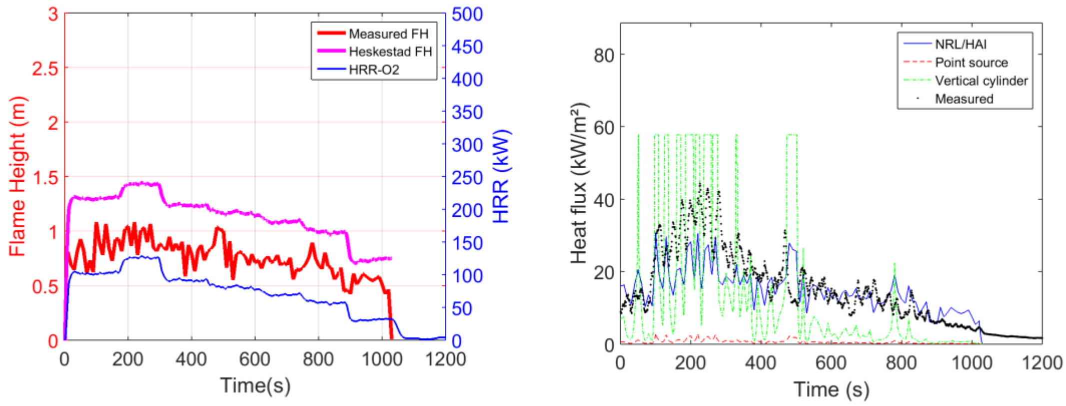
The vertical axis of the heat flux plots has been scaled so that the peak measured heat flux is at 50% of the total height. Predictions greater than 200% of the peak measured heat flux will be off the scale. This is due to the fact that the NRL/HAI correlation is only generally applicable to fires directly against a wall and does not consider separation distances.

The experimental parameter that varies for the data presented in Figure 25 is the horizontal offset of the propane burner from the vertical wall panel. In theory, one could expect that, if the flame is in close proximity to the wall (i.e. for an offset of 150 mm), the entrainment (relatively) would be reduced, the plume would be hotter and the flame height would be greater. The reverse relative trend would apply where the flame plume is offset further away from the wall.

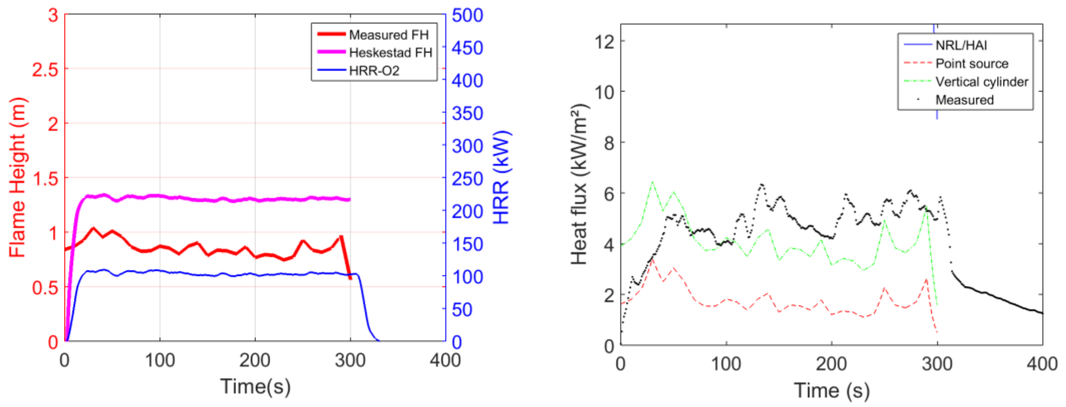
The actual data does not appear to support this hypothesis. With regard to the flame height measurements/predictions shown on the left-hand side of Figure 25, the general trend is that Heskestad's model consistently overpredicts the experimental flame height measurements.

With regard to heat flux comparisons, the best match for Figure 25(a) is the NRL/HAI model. This is not surprising in that the burner-against-the-wall scenario is exactly the basis for the NRL/HAI model, albeit the ISO 9705 burner is smaller than the burner size range used by Back et al. (1994).

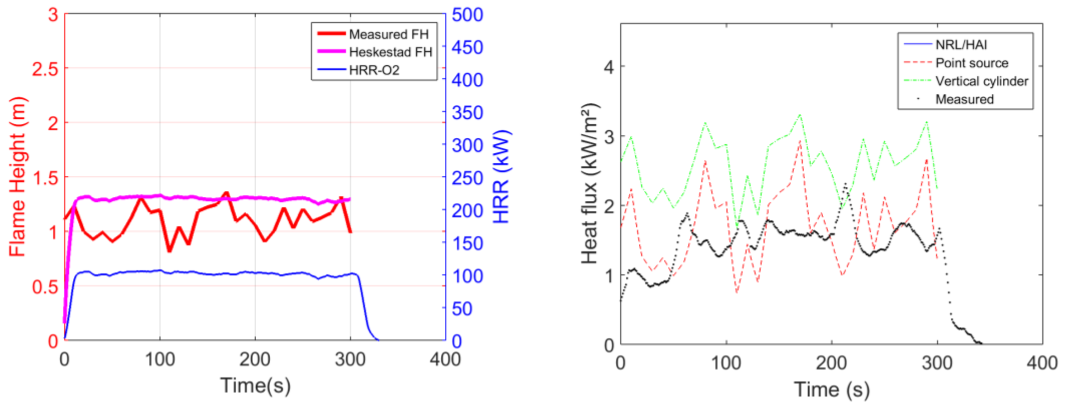
At the other offset positions, the NRL/HAI model significantly overpredicts the heat flux, and the vertical cylinder model gives the best prediction. At an offset of 1.5 m, the measured heat flux value is approaching the level of the measurement accuracy.



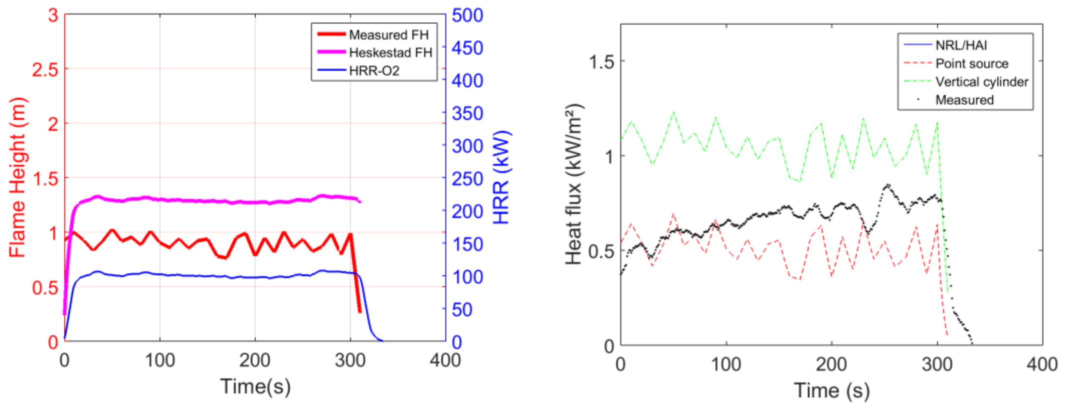
(a) Expt. 1A direct contact (170 mm wall to burner centre)



(b) Expt. 1B 500 mm offset to burner centre



(c) Expt. 1C 1000 mm offset to burner centre



(d) Expt. 1D 1500 mm offset to burner centre

Figure 25. Series 1 free-burn propane experiments – flame height, HRR, heat flux.

5.2 Wood crib free-burn experiments

In experiments 1G–1J (wood), the wood crib was progressively moved further away from the vertical wall, starting hard against the wall (170 mm horizontal offset to crib centre) up to a horizontal offset of 1000 mm (to crib centre).

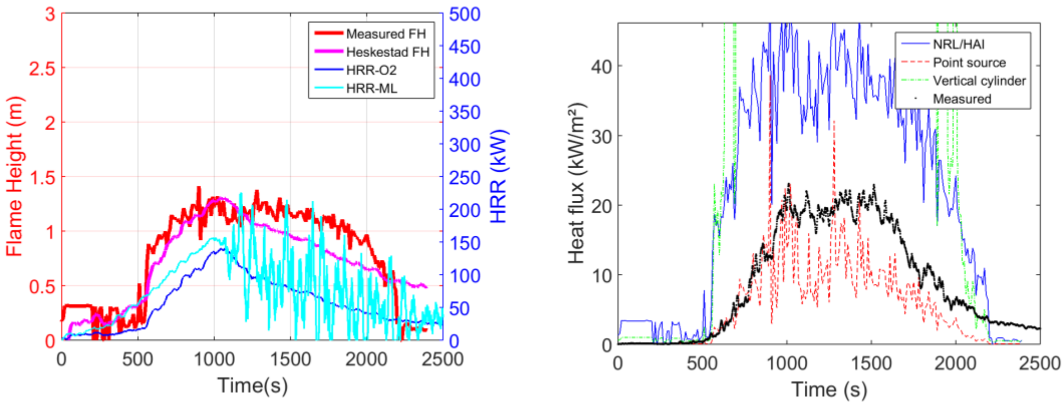
In Figure 26, the graphs on the left-hand side of the figure show measured flame height and the corresponding prediction using Heskestad's correlation (Eq. 3-25), the measured HRR using oxygen consumption calorimetry and the measured HRR using mass loss data. The graphs on the right-hand side show the measured heat flux at the third pHFM, i.e. at 917 mm above the fuel item. This data is compared to the predictive models described in section 3.1.

The comparison between Expt. 1G and 1H (a replicate of 1G) shows reasonable repeatability in the HRR, flame height and heat flux. In fact, over all four experiments, the HRR and flame height does not appear to be significantly affected by the proximity to the vertical wall panel, while the heat flux reduces, as expected, as the wood crib moves further away from the vertical measurement plane. The most likely explanation for the consistency in HRR is that the wood crib acts like a self-contained compartment where the majority of the radiant enhancement driving pyrolysis is from within the crib itself.

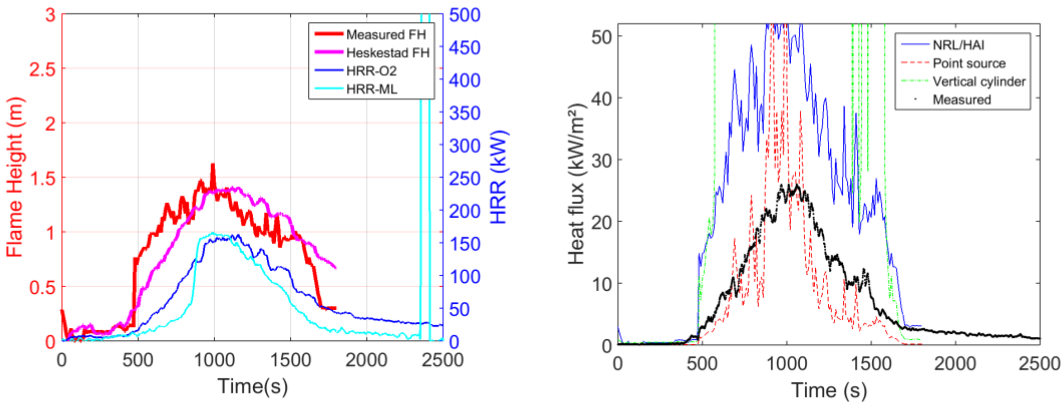
There is also a good match between the Heskestad flame height model and the measured data.

Unlike the propane experiments, the NRL/HAI model does not provide a good match to the measured heat flux data where the wood crib is against the vertical wall panel (Expt. 1G and 1H). The model predicts a peak heat flux that is approximately twice the measured value while the cylindrical model predicts a peak approximately three times the measurement.

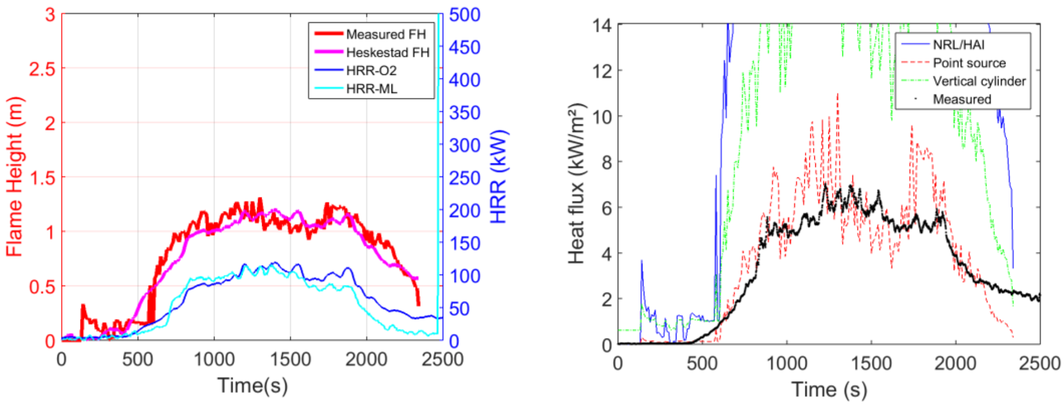
The best match between model prediction and measured data is achieved with the point source model. For the two larger fuel offset experiments (Expt. 1I and 1J), predictably the gap between the NRL/HAI model and the experimental observations increases since the model is a function of the HRR without accounting for the separating distance. The prediction of the cylindrical model improves with increasing offset, but the point source model continues to give the best prediction/measurement match.



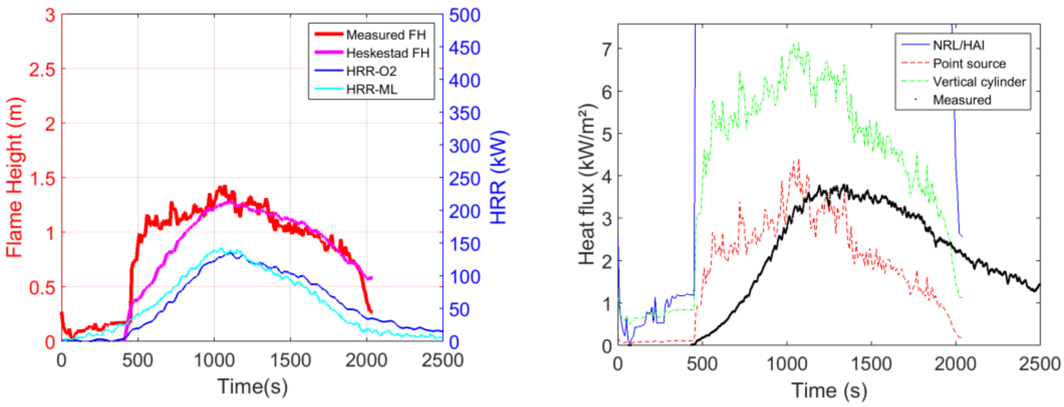
(a) Expt. 1G direct contact (170 mm offset)



(b) Expt. 1H repeat Expt. 1G



(c) Expt. 1I 500 mm offset

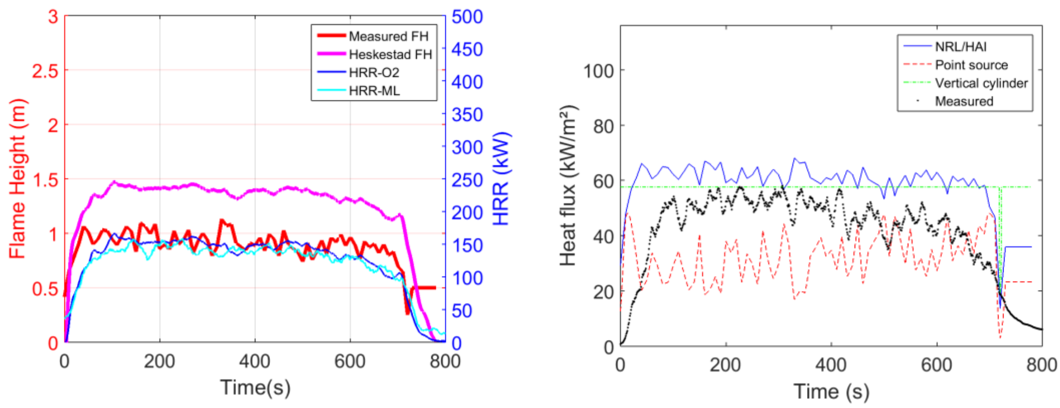


(d) Expt. 1J 1000 mm offset

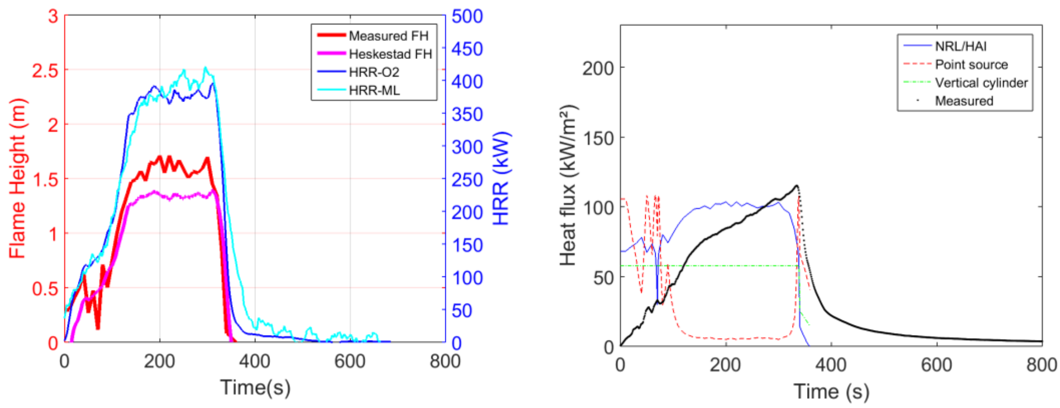
Figure 26. Series 1 free-burn wood experiments – flame height, HRR, heat flux.

5.3 Heptane 300 × 300 mm pan – free-burn and compartment

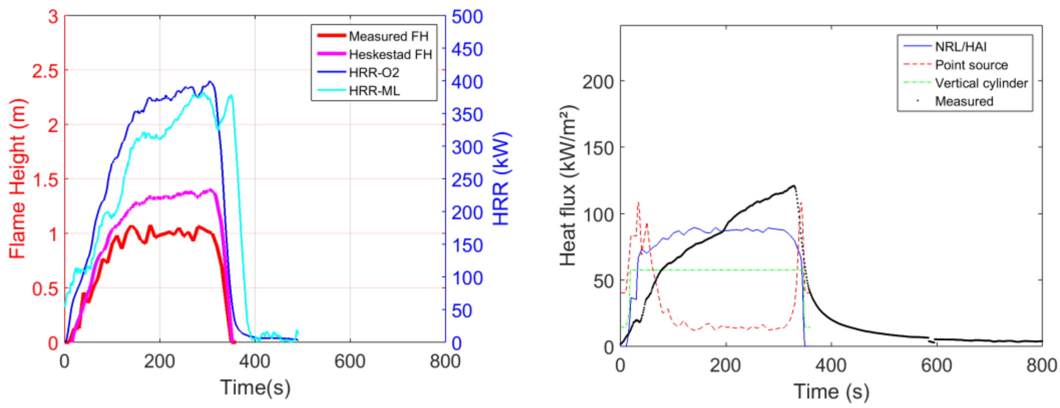
With the heptane 300 × 300 mm pan experiments, three different experimental parameters are varied, namely compartment effects, pan location in the compartment and location of ceiling vent (relative to pan). In Figure 27, the data from Expt. 1E, 2A, 2F, 2B, 3A and 4A are compared. The bottom external heat flux meter (0.317 m above the fuel pan for Expt. 1E and 0.1 m above the ceiling vent in the compartment experiments) and estimated heat flux values are shown on the right.



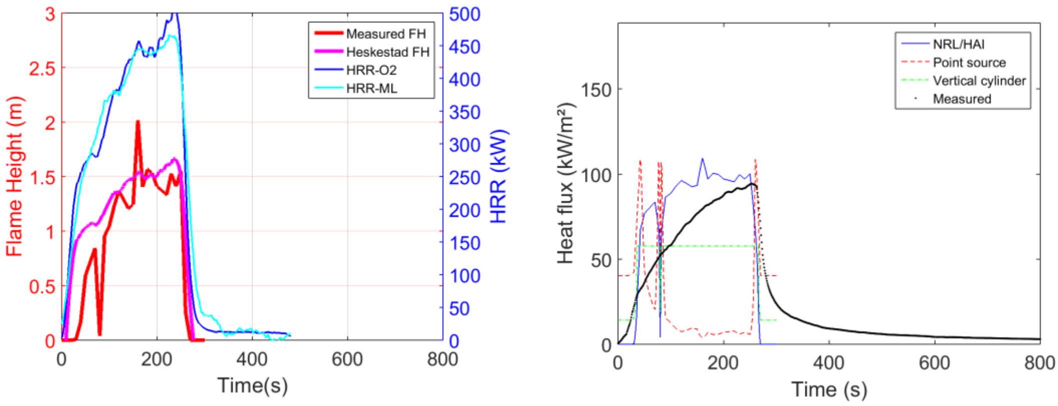
(a) Expt. 1E free-burn 150 mm fuel offset



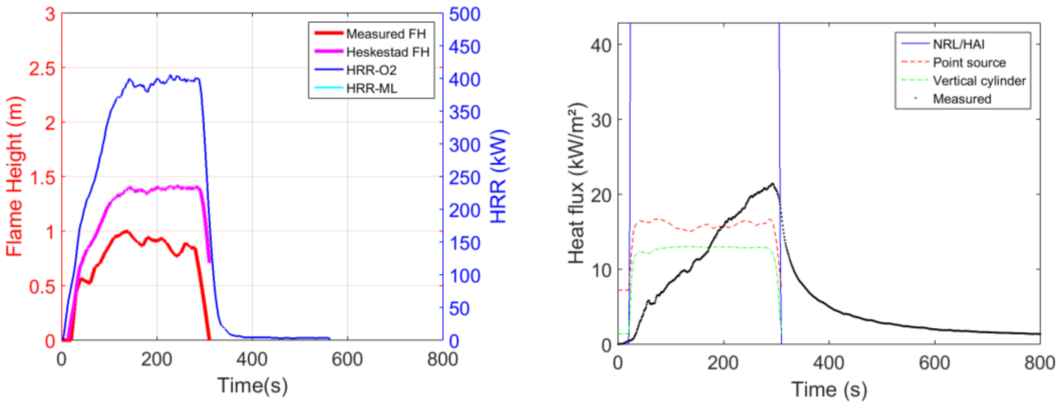
(b) Expt. 2A compartment 150 mm ceiling offset 150 mm fuel offset



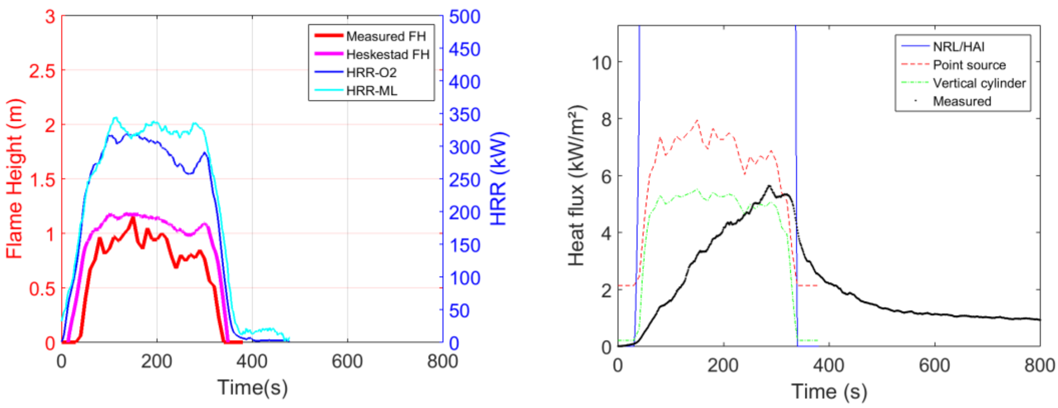
(c) Expt. 2F repeat of Expt. 2A



(d) Expt. 2B compartment ceiling offset 150 mm fuel offset 1050 mm



(e) Expt. 3A compartment ceiling offset 450 mm fuel offset 150 mm



(f) Expt. 4A compartment ceiling offset 850 mm fuel offset 150 mm

Figure 27. 300 x 300 mm pan heptane experiments – flame height, HRR, heat flux.

It is apparent from the data shown in Figure 27 that the compartment is enhancing the HRR. For the free-burn experiment (Expt. 1E), the HRR peaked at approximately 150 kW, while in the compartment experiments (Expt. 2A, 2B, 3A and 4A), the HRR peaked in the approximate range 400–500 kW.

The enhancement of the HRR by the compartment does not give a consistent corresponding increase in the flame height. It is apparent from Expt. 2A and 2B that the compartment has caused the flame height to increase significantly, but then with the replicate of Expt. 2A (Expt. 2F) and Expt. 3A and 4A, no enhancement in the flame height is apparent. There is a reasonably good match between the measured flame height and the prediction of the Heskestad model.

The compartment is also having an impact on the heat flux. Ignoring the connection between magnitude of HRR and heat flux, the compartment also introduces significant additional heat flux over and above the free-burning case.

In Figure 27(a), an approximately constant HRR results in a heat flux that is approximately constant. In contrast, in Figure 27(b), for example, an approximately constant HRR results in a heat flux that continues to grow significantly during the period of constant HRR.

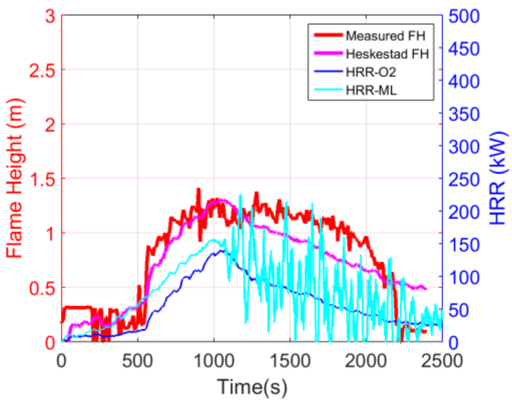
There is also good repeatability in the peak HRR and heat flux for compartment heptane pan tests – the graphs in Figure 27(b) and (c) show good consistency, although not so for the flame height measurements.

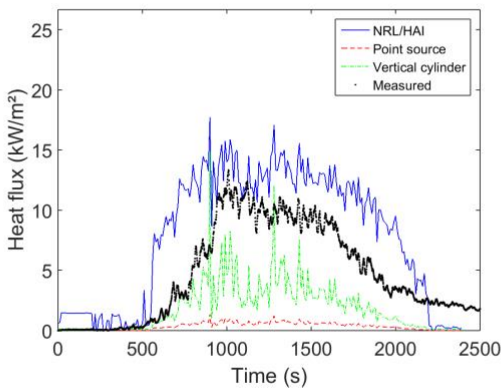
The location of the heptane pan in the compartment also has an impact. Comparing Figure 27(b) and (d), the effect of moving the pan away from the ceiling opening (and closer to the vertical ventilation opening) is to make the fire more intense (higher peak HRR and shorter duration). This is most likely a result of the increased ventilation due to the proximity of the fuel pan to the vertical opening in the front wall.

It is also apparent from the data in Figure 27 that, where the horizontal opening offset (for the compartment experiments) and the fuel pan offset (for the free-burn experiment) is 150 mm (Expt. 2A, 2B and 1E), the measured heat flux is best predicted by the NRL/HAI model. When the horizontal opening offset increases (Expt. 3A and 4A), the vertical cylinder model provides the best match between measured and predicted heat flux.

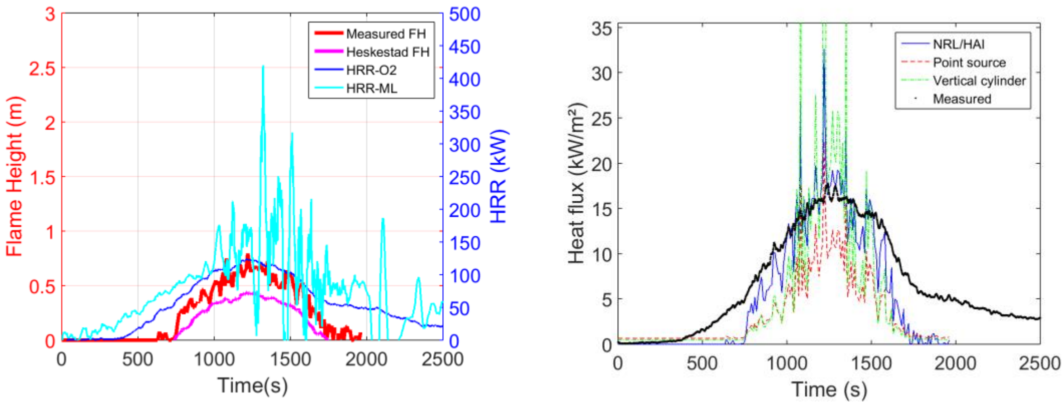
5.4 Wood crib – free-burn and compartment

In Figure 28, the graphs on the left-hand side of the figure show measured flame height and the corresponding prediction using Heskestad's correlation (Eq. 3-25), the measured HRR using oxygen consumption calorimetry and the measured HRR using mass loss data. The graphs on the right-hand side show the measured heat flux at either the fifth pHFM, i.e. at 1517 mm above the fuel item for the free-burn experiment, or the third pHFM (corresponding to approximately 1500 mm from the compartment floor) for the compartment experiments. This data is compared to the predictive models described in section 3.1.

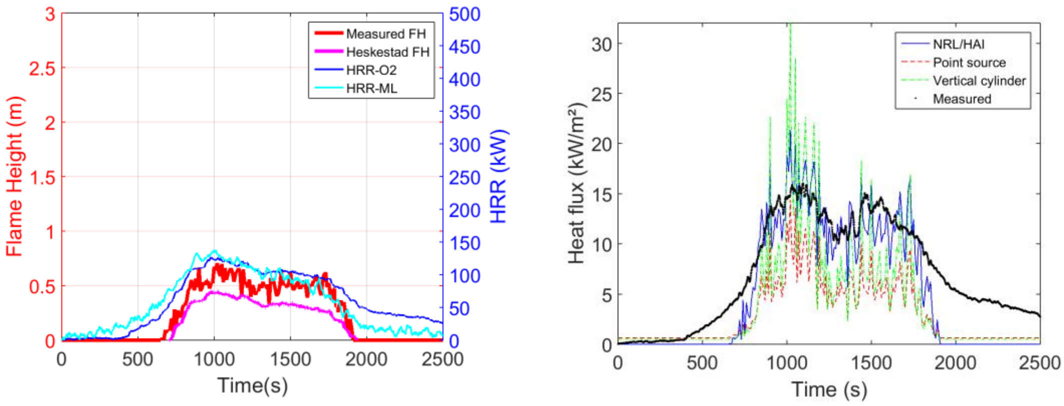




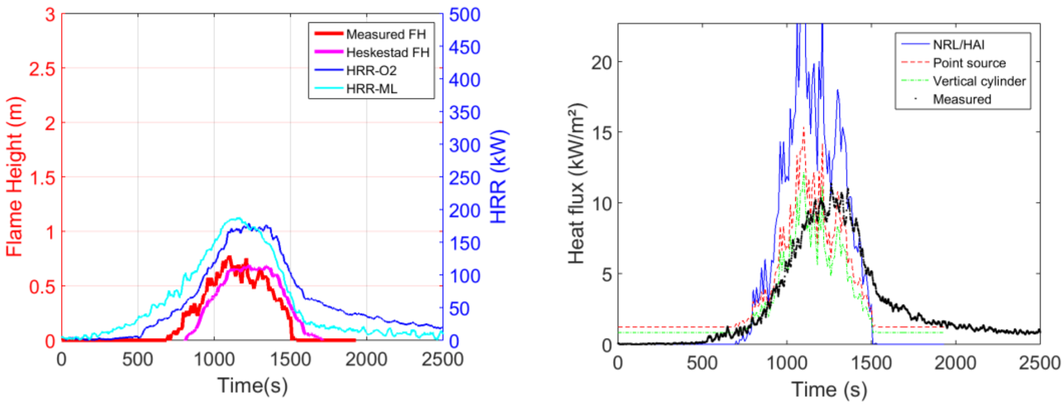
(a) Expt. 1G free-burn fuel offset 170 mm



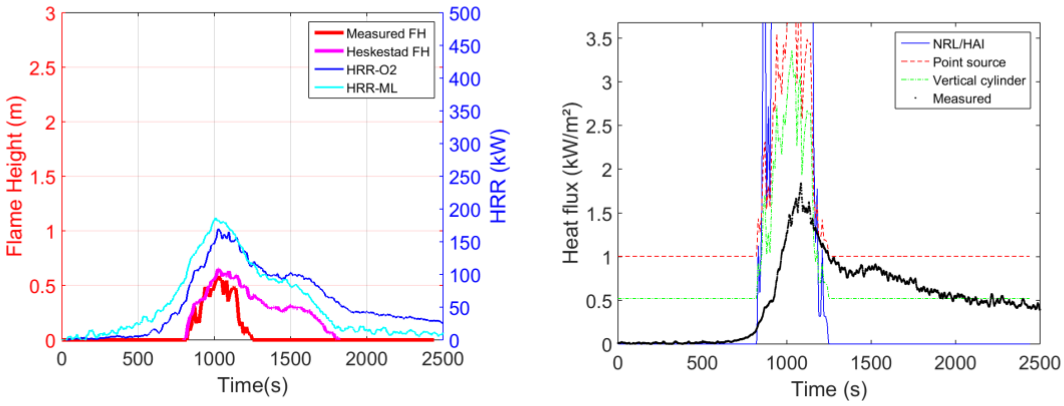
(b) Expt. 2D compartment ceiling opening offset 150 mm fuel offset 150 mm



(c) Expt. 2E repeat of Expt. 2D



(d) Expt. 3C compartment ceiling opening offset 450 mm fuel offset 150 mm



(e) Expt. 4C compartment ceiling opening offset 850 mm fuel offset 150 mm

Figure 28. Wood experiments – flame height, HRR, heat flux.

From the data presented in Figure 28, as with the comparison of the free-burn wood crib experiments in section 5.2, it is apparent that there is a relatively small enhancement of the peak HRR value between free-burn and compartment experiments. The peak HRR value for the free-burn Expt. 1G is ≈ 140 kW, while for compartment Expt. 3C and 4C, it is ≈ 170 kW or a ≈ 20% increase. The explanation for this is linked to the corresponding explanation given for the free-burn experiments, where although there is some overall enhancement from the compartment, the majority is still from within the crib itself. The shape of the HRR curve for the latter also has a steeper growth/decay shape compared to the former. The comparison between Expt. 1G and 2D/2E does not show any enhancement – this is most likely due to the placement of the wood crib directly under the ceiling opening in Expt. 2D/2E minimising compartment effects and hence for all intents and purposes being similar to the free-burn crib against the vertical wall panel in Expt. 1G.

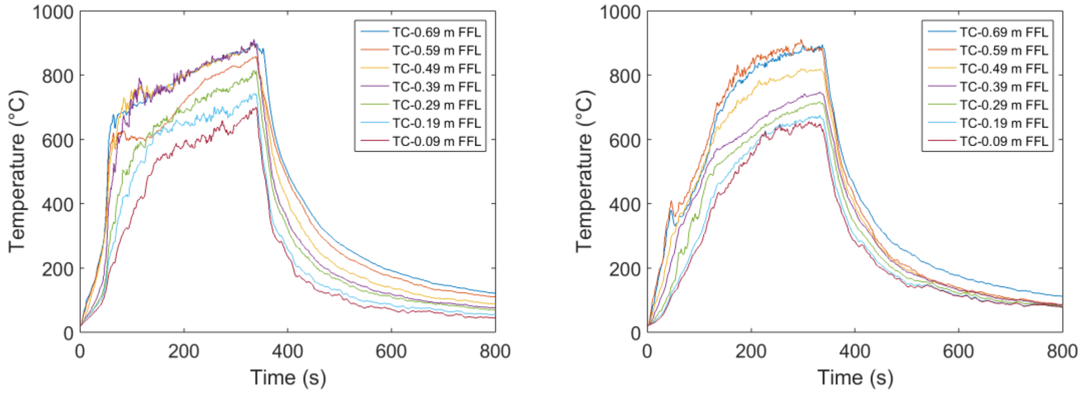
The compartment also appears to reduce the flame height when compared to the free-burn experiment (Expt. 1G). The explanation for this is most likely in the fact that the flame height measurements for the compartment experiments are taken relative to the outer surface of the compartment ceiling as opposed to the base of the wood crib for the free-burn experiment. If an additional allowance of approximately 0.7 m is made for the vertical distance between the top of the fuel bed in the compartment and the outer surface of the compartment ceiling, the adjusted peak flame heights for the compartment experiments would be similar to those for the free-burn experiment.

The measured flame height reached a steady state peak plateau for the free-burn and 150 mm fuel offset compartment experiments. Conversely, the measured flame height increased to a peak and then declined for the 450 mm and 850 mm fuel offset compartment experiments, never achieving a stable value. This is again linked to the HRR aspects noted already where Expt. 3C/4C have a more pronounced peak in the HRR curve. There is also generally a good match between the measured flame height and the Heskestad model.

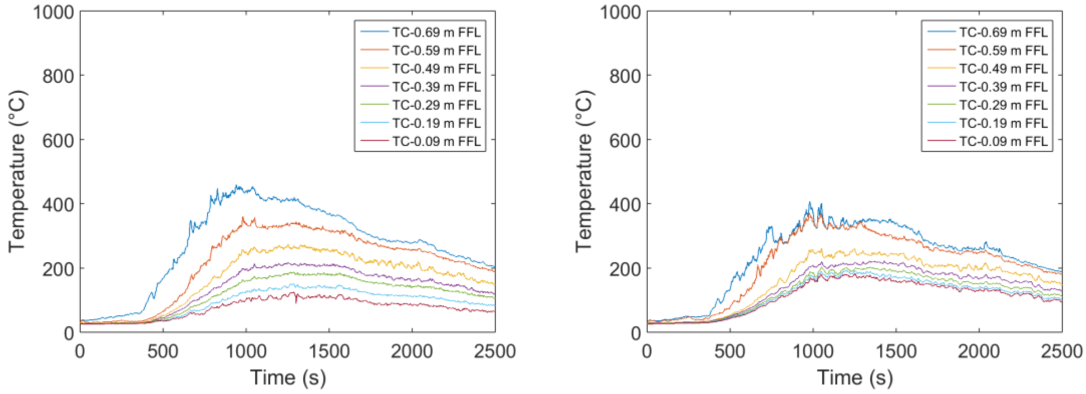
At the heat flux meter heights shown, the NRL/HAI provided the best prediction of heat flux for fire sources directly adjacent to the wall. The peak heat fluxes at the bottom of the wall were not predicted well by any of the models. Where the ceiling opening is offset from the vertical wall panel (Expt. 3C and 4C), the cylindrical model gives a good match with the measured data.

5.5 Compartment temperatures

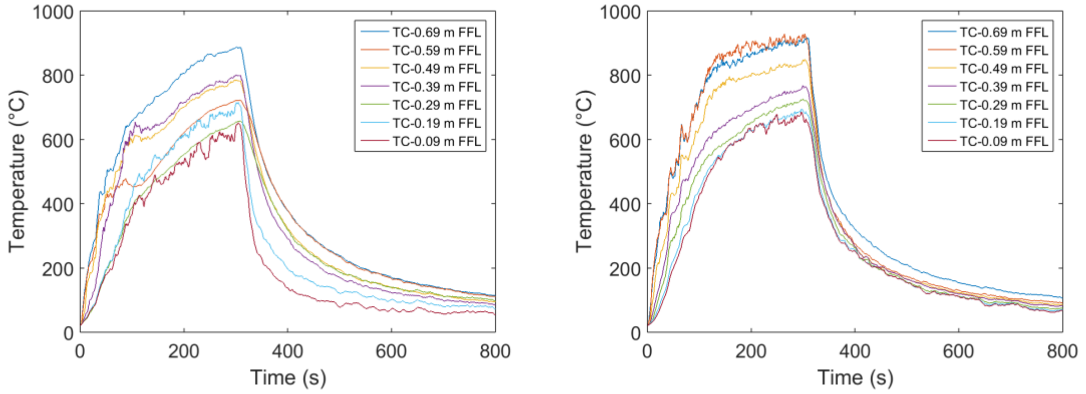
Two different fuel types were used in the compartment experiments (Series 2–4). The graphs on the left-hand side of Figure 29 show the thermocouple readings at the front of the compartment, while the right-hand graphs show the corresponding readings at the rear of the compartment. The compartment temperatures were highest in the heptane experiments, reaching up to 1000°C. Increases in peak temperatures in the heptane compartment experiments as the ceiling vent was moved were minimal, because they were already near typical flame temperatures. Peak temperatures in the wood crib experiments were as low as 450°C when the wood crib was positioned right below the ceiling vent. As the wood crib location was offset, the compartment temperatures increased due to the longer residence time of flames and hot gases in the compartment before escaping through the ceiling vent. This likely contributed to the slight HRR enhancement, but as mentioned before, was minimal because most of the wood crib surfaces would not have been affected.



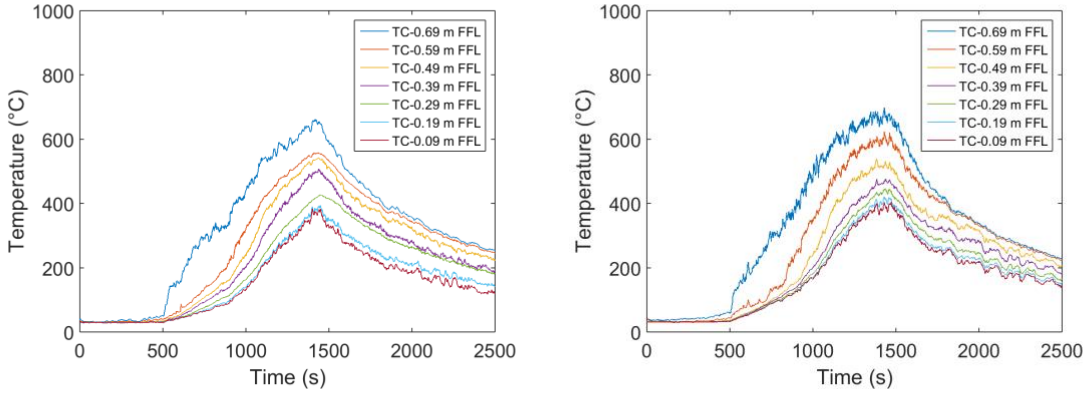
(a) Expt. 2A heptane ceiling opening offset 150 mm fuel offset 150 mm



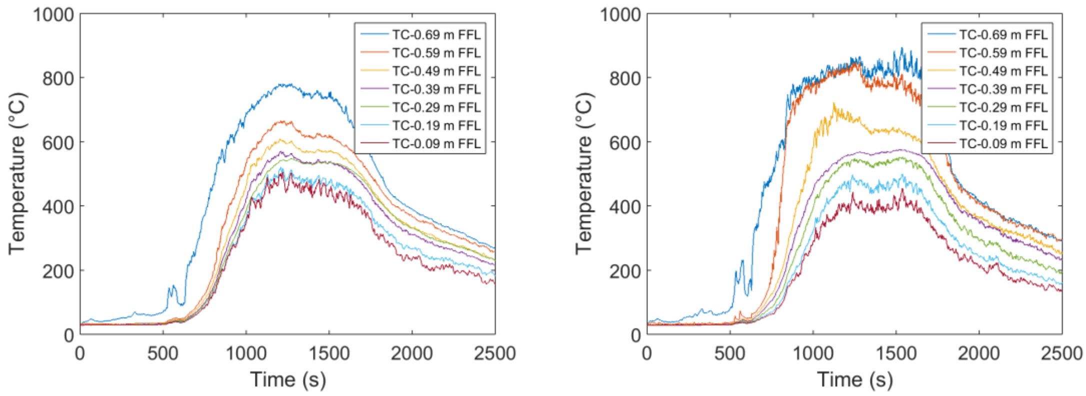
(b) Expt. 2D wood ceiling opening offset 150 mm fuel offset 1050 mm



(c) Expt. 3A heptane ceiling opening offset 450 mm fuel offset 150 mm



(d) Expt. 3C wood ceiling opening offset 450 mm fuel offset 150 mm

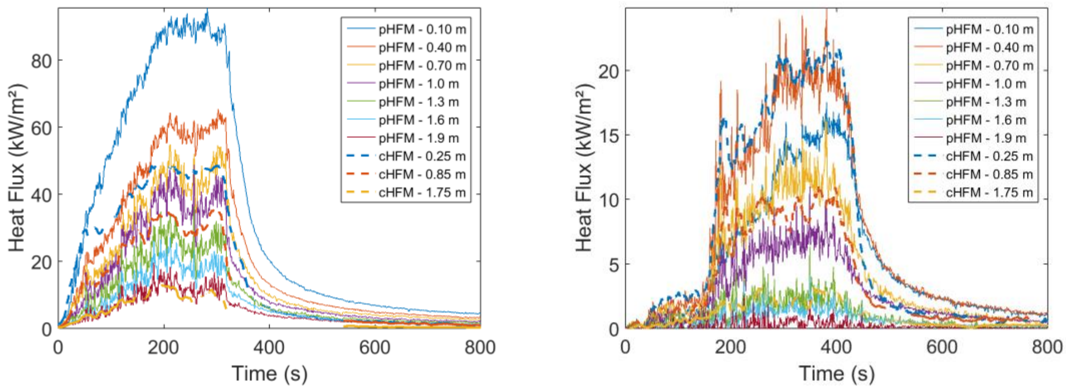


(e) Expt. 4C compartment ceiling opening offset 850 mm fuel offset 150 mm

Figure 29. Example compartment temperatures.

5.6 Comparison of plate and commercial heat flux meters

The plate heat flux meter measurements tended to be higher when compared to the adjacent commercial heat flux meters, particularly at high heat fluxes. Because the measurements are by necessity taken at different locations, it was difficult to determine how much of the difference was due to the meters themselves. For example, Figure 30(a) shows how the bottom commercial heat flux meter (cHFM – 0.25 m) was in good agreement with the adjacent plate heat flux meters (pHFM – 0.1 m and 0.4 m) until the heat flux reached approximately 50 kW/m², at which time the plate heat flux meter measurements continued to climb while the commercial heat flux meter remained relatively constant.



(a) Experiment 2H (b) Experiment 3B

Figure 30. Plate and commercial heat flux meter measurements.

The heat flux meters that were measuring lower heat fluxes (either higher up the wall or when the fire source was farther from the wall) showed good agreement. For example, the same cHFM – 0.25 m was in excellent agreement with pHFM – 0.4 m in Expt. 3B as shown in Figure 30(b). The heat flux measured by pHFM – 0.1 m was lower, which was expected due to the heat flux profile when the ceiling vent is separated from the wall.

One observed issue with the commercial heat flux meters was the build-up of soot on their measurement faces as shown in Figure 31. This is partially due to the use of cooling water in the commercial heat flux meters, which provides a cooler surface for soot to accumulate on when the heat flux meters are in direct flame contact. This was also the issue observed with the commercial radiometers as their windows could not be kept clean with the air purge. This would tend to reduce the heat flux measured by the commercial heat flux meters as the soot would provide an insulating effect. Discussions with the manufacturer indicated that attempts to clean the soot off the surface would potentially damage the delicate sensor surface. Calibrations in the cone calorimeter up to 100 kW/m² after the Series 2 experiments suggested that the sensor sensitivity was not adversely affected.

Figure 31. Soot build-up on commercial heat flux meters.

5.7 Correlation evaluation summary for fires from lower roofs based on small-scale experiments

The primary goal of the experimental programme for this project was to investigate whether the proposed theoretical models could be applied to the fire spread from lower roofs problem. The following sections discuss how well the flame height and heat flux correlations were able to match the measured values in the reduced scale experiments.

The method used by NIST for the FDS Validation Guide (McGrattan et al., 2016) and other publications for correlation validation (Overholt, 2014) was used to determine model bias and standard deviation. The plots in the following section use the convention of a solid line for the equality line (estimated value = measured), dashed lines at ± two times the model standard deviation and a coloured dotted line representing the model bias.

5.7.1 Flame height

A linear density scatter plot for the time-varying flame heights from all experiments is shown in Figure 32. The colour of each hexagon represents the number of data points included in the hexagon area. The experimental uncertainty standard deviation was estimated to be 10% based on the video flame height 50% intermittency calculation. The initial and final periods of flame height data during growth and decay were removed from each of the experiments. The compartment height was added to the flame heights for compartment experiments.

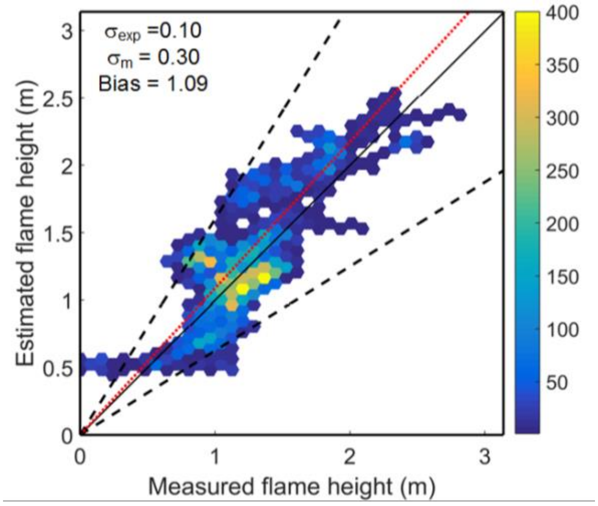
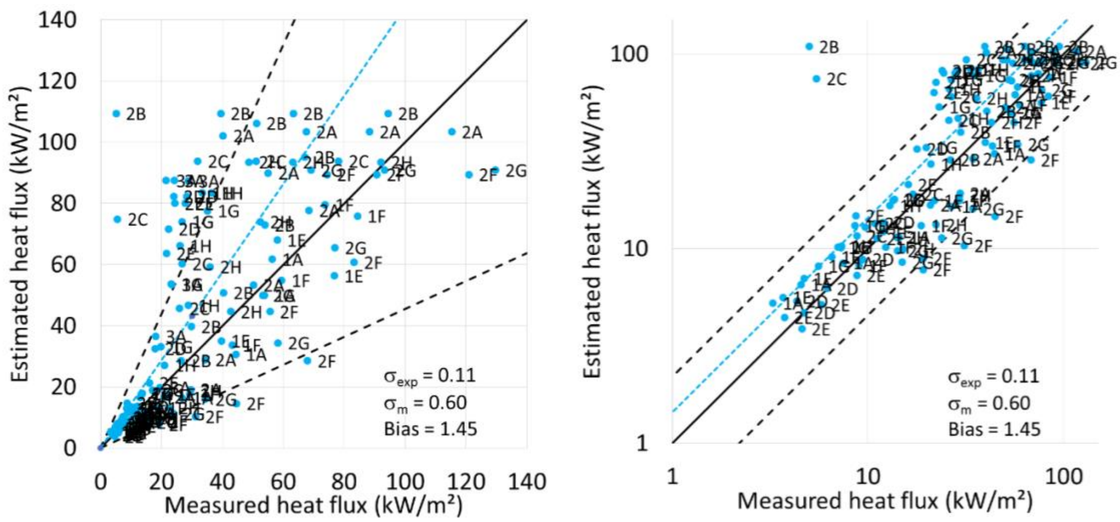


Figure 32. Estimated versus measured flame heights.

The Heskestad flame height correlation discussed in section 3.2.1 tended to slightly overpredict flame height (bias of 1.09), and the model standard deviation was calculated to be 30%. The methodology presented by NIST was used for the bias and standard deviation calculations (McGrattan et al., 2016). Some of the spread can be attributed to fluctuations in flame height and heat release rate that weren't always in sync. This means that heat release rates might be slightly underpredicted when back calculated from flame heights, as proposed in section 3.2.1.

5.7.2 Heat flux correlations

A standard deviation of 11% for the experimental uncertainty in the heat flux measurements is again based on the methodology presented by NIST (McGrattan et al., 2016). The uncertainty may have been slightly higher at high heat fluxes as noted in section 5.6. In general, the NRL/HAI correlation did not work well for fire sources separated horizontally from the upper wall, as expected. Therefore, the comparison was limited to experiments where the fire or ceiling vent was directly adjacent to the wall. Comparisons of peak heat fluxes from each heat flux meter in these experiments are shown in Figure 33. The experiments are labelled on the data points.

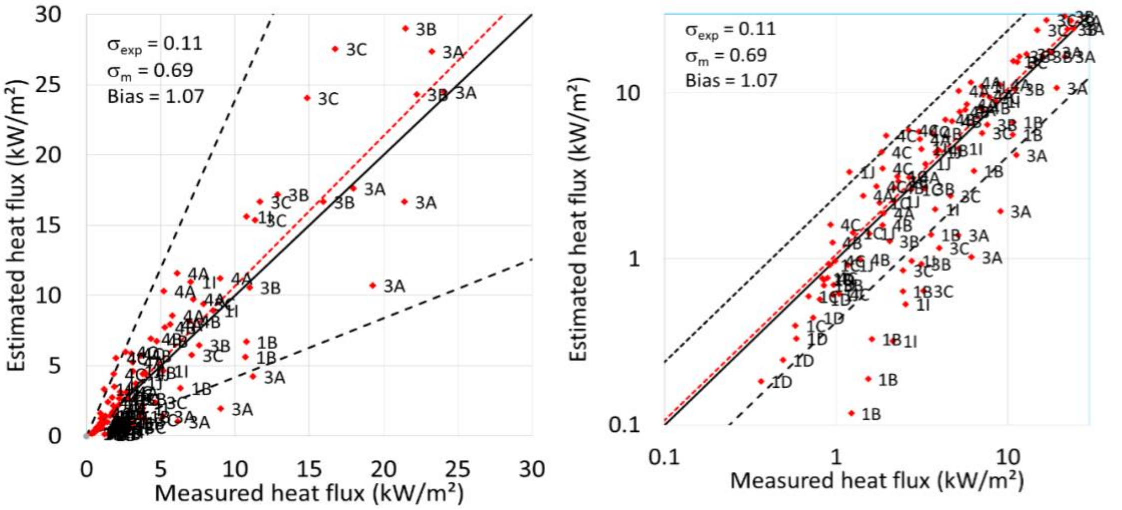


(a) Linear scale (b) Log-log scale

Figure 33. Estimated versus measured peak heat flux: NRL/HAI.

Two outliers for heat flux for Expt. 2B and 2C resulted from faulty heat flux measurements for one of the pHFMs, which was subsequently corrected in the other experiments. The NRL/HAI correlation tended to overpredict the heat flux particularly for the compartment experiments, with a bias of 1.45. There was quite a bit of spread in the results as well, with a model standard deviation of 60%.

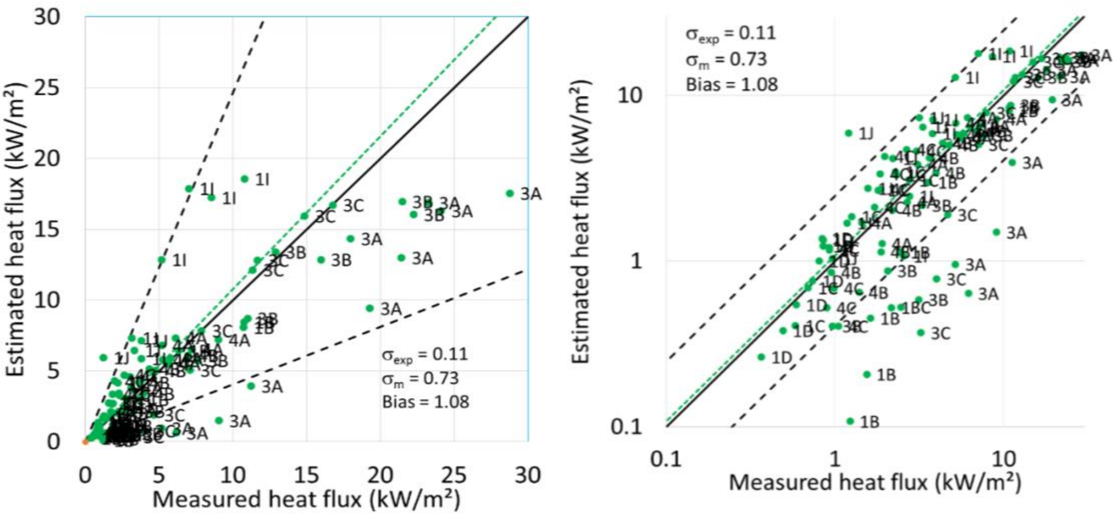
The point source and vertical cylinder correlations did not work particularly well for the fires where the source was directly adjacent to the wall but did work well when the fire was separated. Comparisons for the horizontally separated fire source experiments are shown for the point source and vertical cylinder models in Figure 34 and Figure 35 respectively. Both models tended to slightly overpredict heat flux (bias of 1.07 for the point source model and 1.08 for the vertical cylinder model), and both had significant spread (model standard deviation of 69% for the point source model and 73% for the vertical cylinder model).



(a) Linear scale (b) Log-log scale

Figure 34. Estimated versus measured peak heat flux: point source model.

There did appear to be a transition zone where the point source and vertical cylinder models overpredicted, but the NRL/HAI model underpredicted the heat flux. This can be observed in the peak heat flux values for Expt. 1B and 3A, 3B and 3C.



(a) Linear scale (b) Log-log scale

Figure 35. Estimated versus measured peak heat flux: vertical cylinder model.

5.8 Conclusions

This section has presented results from the reduced-scale experimental programme that was conducted to provide an initial dataset for specifically validating the engineering correlations described in section 3 for the fire spread from lower roofs scenario. It is up to the model user to decide whether the different modelling approaches provide sufficient accuracy to represent fire spread from lower roofs and how much conservatism or safety factor to apply. While this experimental dataset does provide some indication of model performance, caution is recommended when extrapolating to the larger geometries likely encountered in building fire safety design. Future work to develop experimental validation data at larger scales is necessary to improve confidence in model performance. Section 6 compares the model predictions using hypothetical building-scale geometries with prescriptive regulatory requirements.

6. Engineering design methods

This section applies the methods described in section 3 to hypothetical building-scale geometries and compares the predicted thermal exposure to prescriptive regulatory requirements. Note that this does not constitute validation of the models at these scales but is included for comparison only.

6.1 Estimated heat release rates based on flame heights

By rearranging Heskestad's flame height correlation discussed in section 3.2 (Eq. 3-25), an estimate for the heat release rate for flames of a certain height from a roof vent of a certain size can be obtained as shown in Figure 36 and Figure 37. A 10 m by 10 m opening with 10 m tall flames (i.e. the base of the flames is the roof level) is estimated to correspond to an HRR of 85 MW.

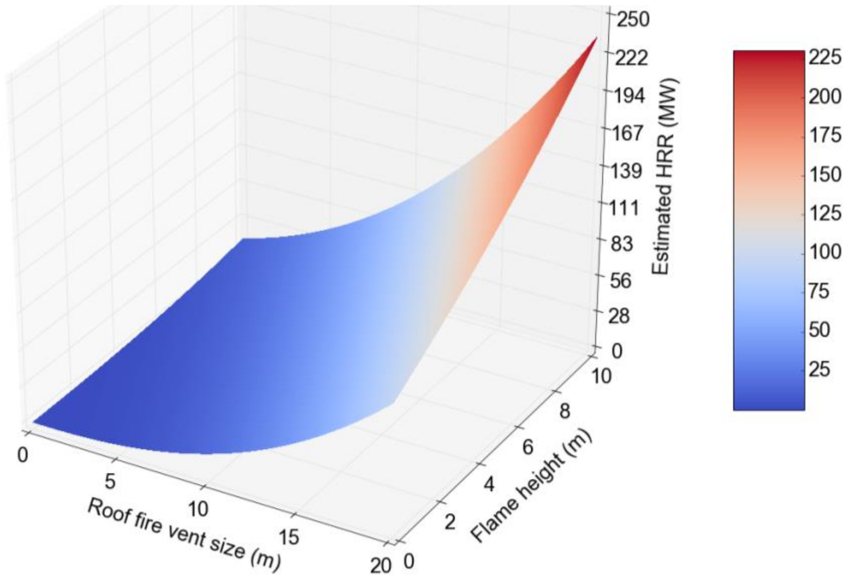


Figure 36. Estimated HRR for different square roof vent and flame height geometries (surface plot).

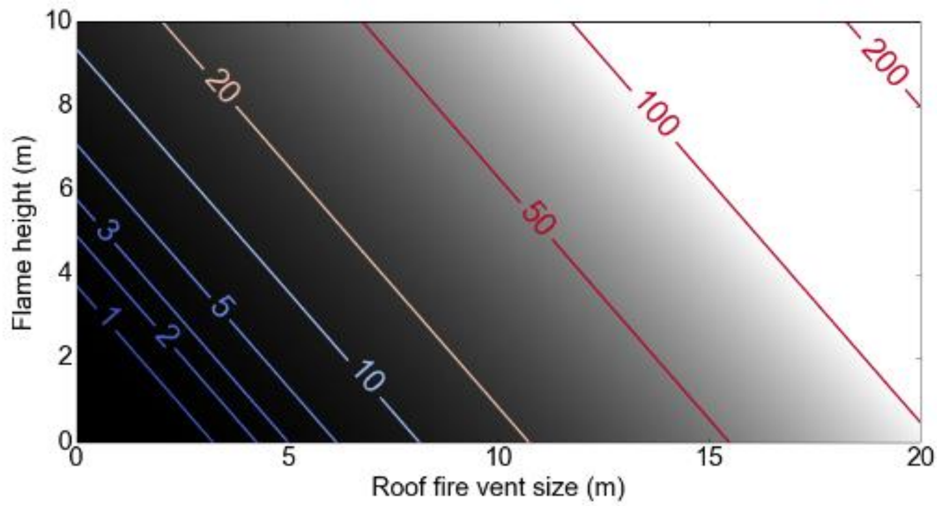


Figure 37. Estimated HRR (in MW) for different square roof vent and flame height geometries (contour plot).

This approach does not consider the heat released within the compartment, which will depend on the compartment geometry. The base of the fire is therefore considered to be roof level. While the heat released in the compartment would not contribute as much to the incident heat on the upper wall, it would be necessary to consider if the entire heat release rate of the fire was required (perhaps for comparative purposes).

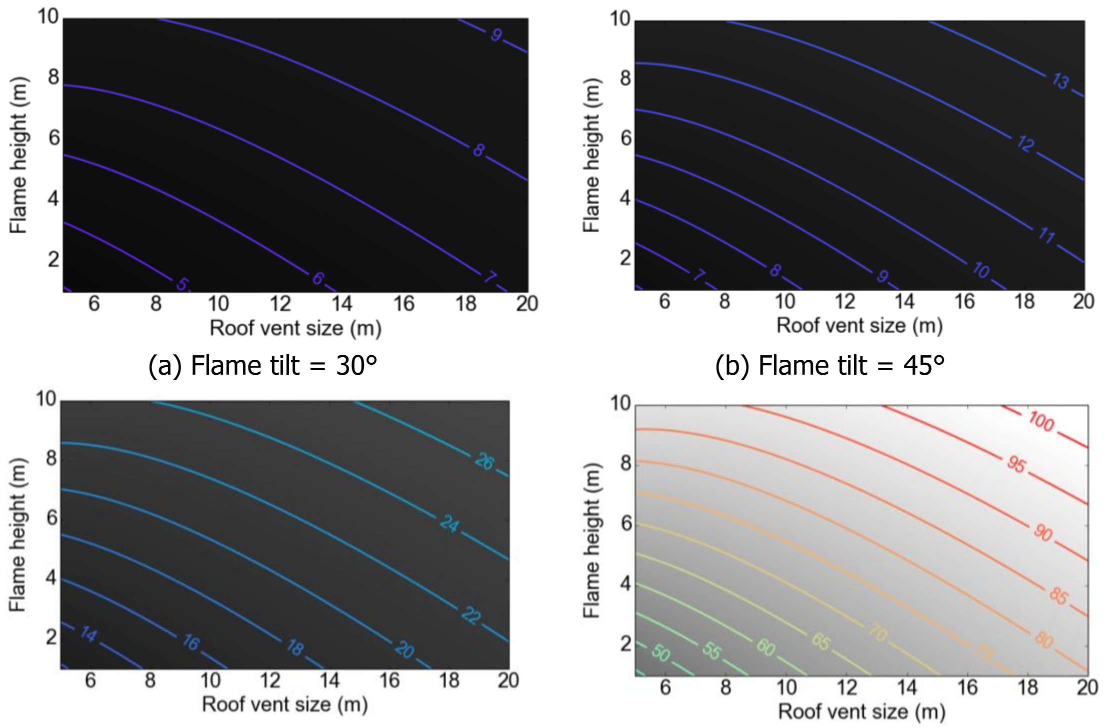
While no data or estimates of the HRR for fully involved buildings with roof-venting flames have been identified, a comparison with typical HRRs for common fuel packages may provide some confirmation of order of magnitude. For example, a typical three seat sofa free-burn total heat release rate of 3 MW (NFPA, 2014) would roughly result in a 2 m high flame from a 3 × 3 m opening using the method depicted in Figure 20 or a 1 m high flame from a 4 × 4 m opening. A multiple workstation experiment by NIST (2004) in a 7.0 × 7.3 × 3.4 m enclosure resulted in a peak total HRR of 19 MW, which would correspond to a flame height of approximately 4 m when the total floor area is considered as an opening. An image of the fire when the total HRR was approximately 15 MW (corresponding to a flame height of approximately 3 m) is shown in Figure 38.

Figure 38. Multiple workstation fire – HRR approximately 15 MW (Madrzykowski & Walton, 2004).

Using the flame height estimates from NFPA 80A, a design fire could be developed for a given scenario as described in the following example. A non-rated lower roof is adjacent to a higher external wall. The largest fire compartment adjacent to the wall is comprised of the top storey (each storey is 3 m) and has plan dimensions of 8 × 8 m. This would give an estimated flame height of 1.4 × 3 m = 4.2 m. By working back through Heskestad's correlation, this would result in 26 MW contributing to the heat incident on the wall above the roof.

6.2 Flame tilt wind velocities

The required wind velocity to achieve a specific flame tilt angle can be estimated using the AGA correlation and the heat release rates obtained from Heskestad's flame height correlation. Figure 39 shows the velocities required to create a flame tilt at a range of angles from 30° to 75° and for a range of roof vent sizes. The wind velocity required for a flame tilt angle of up to 45° is quite low (below 15 km/hr) but then increases quickly above 60°.



(a) Flame tilt = 30°

(b) Flame tilt = 45°

(c) Flame tilt = 60°

(d) Flame tilt = 75°

Figure 39. Required wind velocities (km/hr) for a range of flame tilt angles.

6.3 Comparison of predicted heat flux on a wall adjacent to a fire

Using the radiation and flame height models discussed in sections 3.1 and 3.2, predictions of heat flux on a wall from roof flames nearby can be made. Using the example above of an 8 m square single-storey compartment with an unrated roof, a comparison of the heat flux models can be made. A radiant fraction of 0.35 is assumed for the point source model. Figure 40 shows the comparison of the point source, vertical cylinder and NRL/HAI models along with an allowable heat flux level of 16 kW/m² assuming no separation between the unrated roof and the adjacent wall.

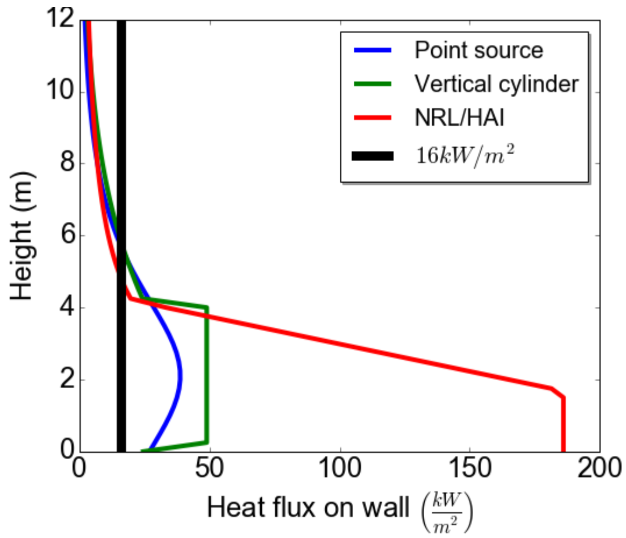


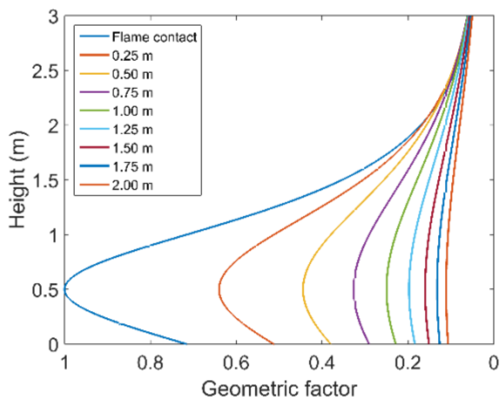
Figure 40. Comparison of point source, vertical cylinder and NRL/HAI heat flux predictions for 8 m square fire compartment example (4.2 m flame height).

Note that, while the NRL/HAI model predicts significantly higher heat flux on the wall adjacent to the flame, the vertical location on the wall where the heat flux drops below the allowable level is reasonably consistent between the three models, approximately 5.5–6 m. The NRL/HAI correlation has the characteristic of always predicting a heat flux of 20 kW/m² at the tip of the flames, regardless of fire size.

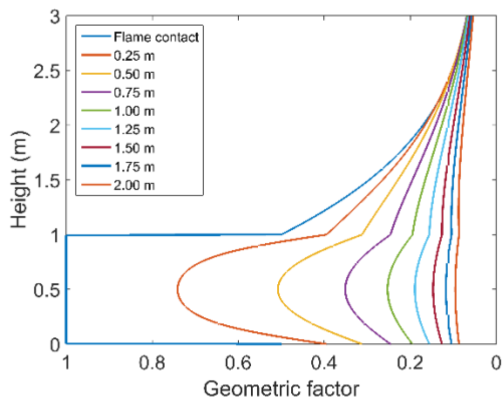
The generalised contours for the point source and vertical cylinder can be compared for a range of radial distances as shown in Figure 41. This figure shows the comparison of the vertical cylinder view factor $F_{12,V}$ with a geometric factor for the point source as follows:

$$GF_{point\ source} = \frac{L}{(H^2 + L^2)^{\frac{3}{2}}} \qquad \textbf{Eq. 6-1}$$

This comparison is made for a theoretical fire 2 m in diameter (which gives a radius of 1 for the point source model at the point of contact at the flame mid height) with a flame height of 1 m. The vertical cylinder model always gives a view factor of 1 on the edge of the flame cylinder except at the very top and bottom where the view factor is 0.5. Therefore, on the cylinder edge, the predicted heat flux is always equal to the emissive power. The predicted heat flux drops very quickly above the top of the flame cylinder. The point source model does not predict a constant heat flux in contact with the flame and has a more gradual taper above the tip of the flame. The contours become increasingly similar as the distance from the flame increases.



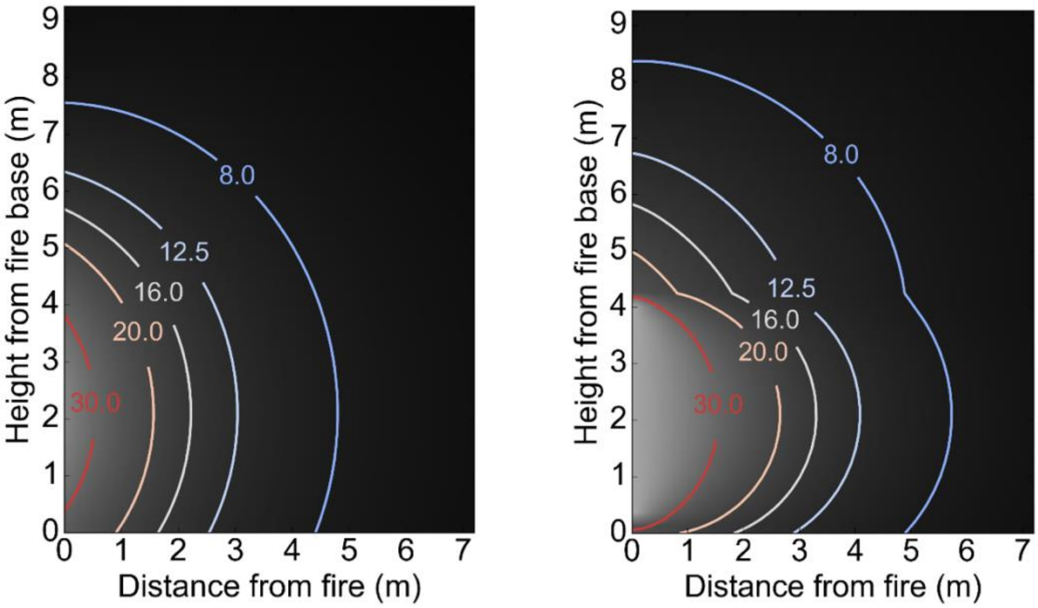
(a) Point source



(b) Vertical cylinder

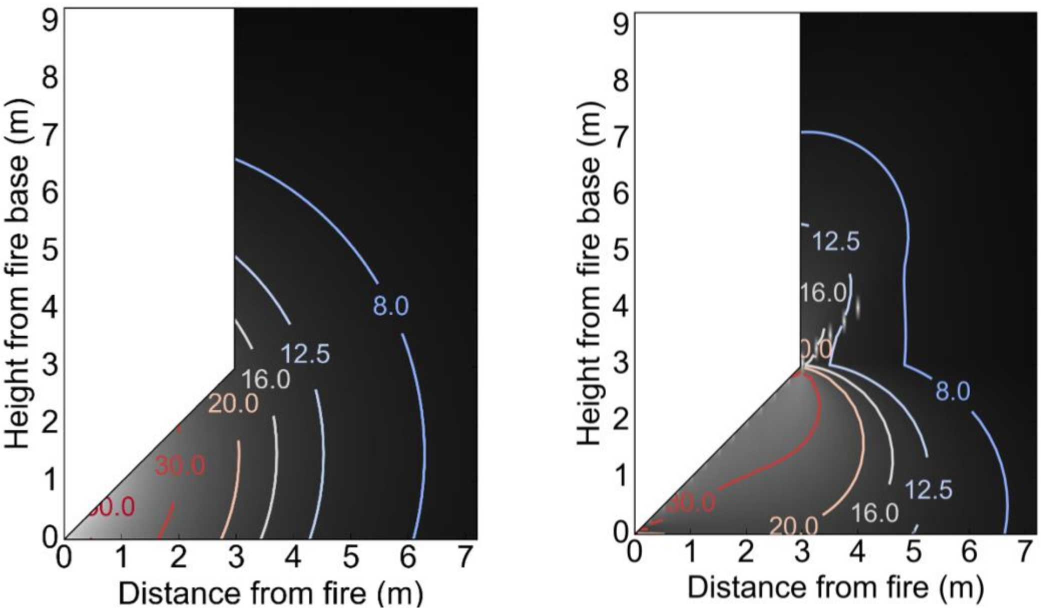
Figure 41. Point source and vertical cylinder geometric factor comparison.

The peak heat flux for the vertical cylinder is only a function of the effective diameter of the fire, while the peak heat flux for the point source is also a function of the HRR. For this flame geometry (back calculating the HRR using the flame height correlation described in section 3.2.1), the point source model estimates the peak heat flux to be 16.7 kW/m², compared to 55 kW/m² predicted by the vertical cylinder model. The flame height would have to be approximately 2.85 m for the point source to predict a peak heat flux of 55 kW/m². The NRL/HAI correlation peak heat flux is only a function of the HRR and predicts a peak heat flux of 106 kW/m² for the 1 m tall flame and 135 kW/m² for the 2.85 m tall flame. Considering separation, contour maps of the expected heat flux on the wall can be made based on separation distance and height on the wall above the roof, as shown in Figure 42 for a vertical flame and Figure 43 for a 45° tilted flame. The maximum heat flux occurs at half the flame height, i.e. 2.1 m for flames from a single storey compartment.



(a) Point source (b) Vertical cylinder

Figure 42. Point source and vertical cylinder heat flux map for example of 8 m square roof vent.

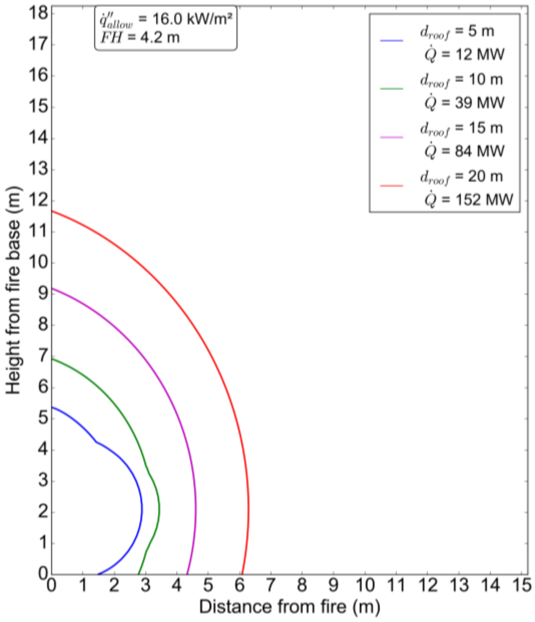


(a) Point source (b) Tilted cylinder

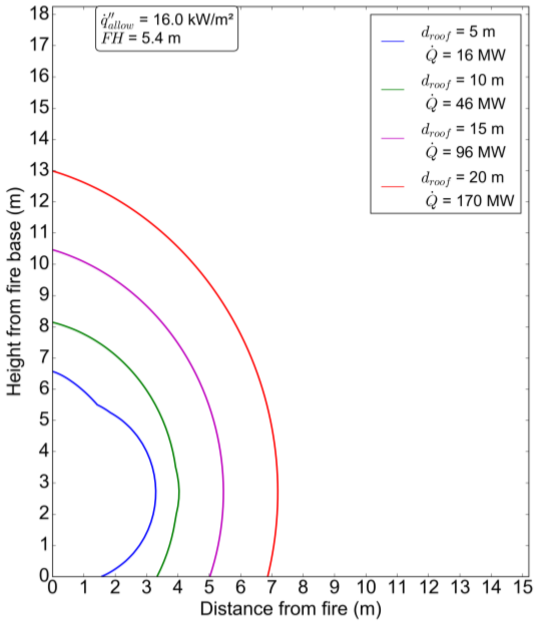
Figure 43. Point source and tilted cylinder heat flux estimates for 8 m square single-storey fire compartment with a 45° tilted flame.

The white regions in Figure 43 represent areas where direct flame impingement (or above) would be expected. The discontinuities in the cylindrical models represent where contributions from the top cylindrical surface are added where the height is above the flame 'cylinder' height of 4.2 m. For this example, using 16 kW/m² as the criteria results in a required protected height of 6 m or a separation requirement of 5 m, while using 12.5 kW/m² as the criteria results in a required protected height of 7 m or a separation requirement of 5.5 m. The point source model and cylindrical models provide similar heat flux envelopes, particularly at lower heat flux levels. In general, the cylindrical model is slightly more conservative, predicting higher heat fluxes for a given position.

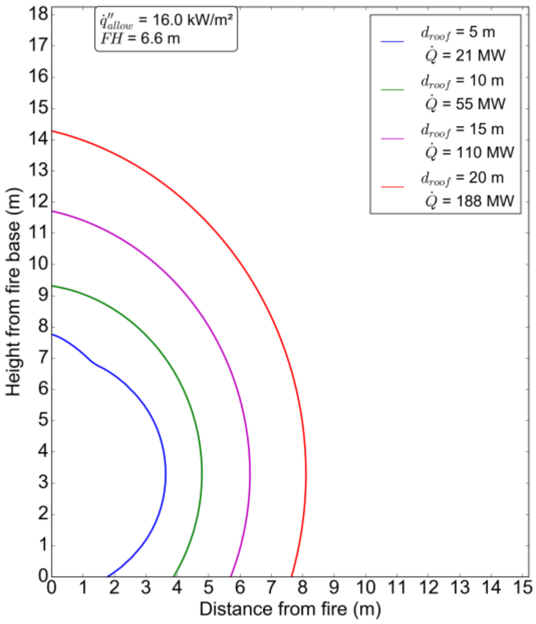
Another way of visualising this data is to plot individual heat flux contours for different sizes of fires. In Figure 44 and Figure 45, the heat flux field is calculated using both the point source and the cylindrical models, and the maximum value is chosen at each point. Figure 44 shows 16 kW/m² contours for 1, 2, 3 or 4 storeys of the building contributing to the fire, with 5 m, 10 m, 15 m and 20 m square roof vents. A 15 × 15 m roof vent with 1 storey contributing is estimated to produce 16 kW/m² at 9 m vertically and 5 m horizontally. Another scenario that produces approximately the same envelope is a 10 m square roof vent with 3 storeys contributing. Figure 45 shows 12.5 kW/m², 16 kW/m², 20 kW/m² and 30 kW/m² heat flux contours for 1 storey contributing and the same roof vent sizes as in Figure 44. Of particular note is that the comparable 12.5 kW/m² contour for a 15 × 15 m roof vent with 1 storey contributing is 10 m vertical and 6 m horizontal, which matches the DZ 4226:1984 requirements.



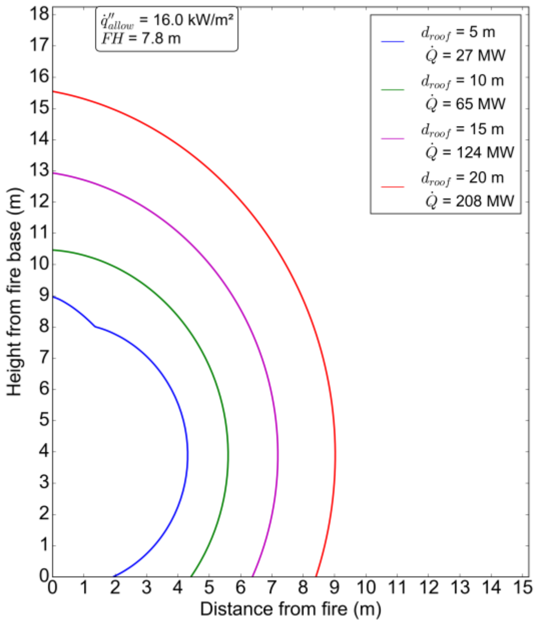
(a) 1 storey contributing



(b) 2 storeys contributing

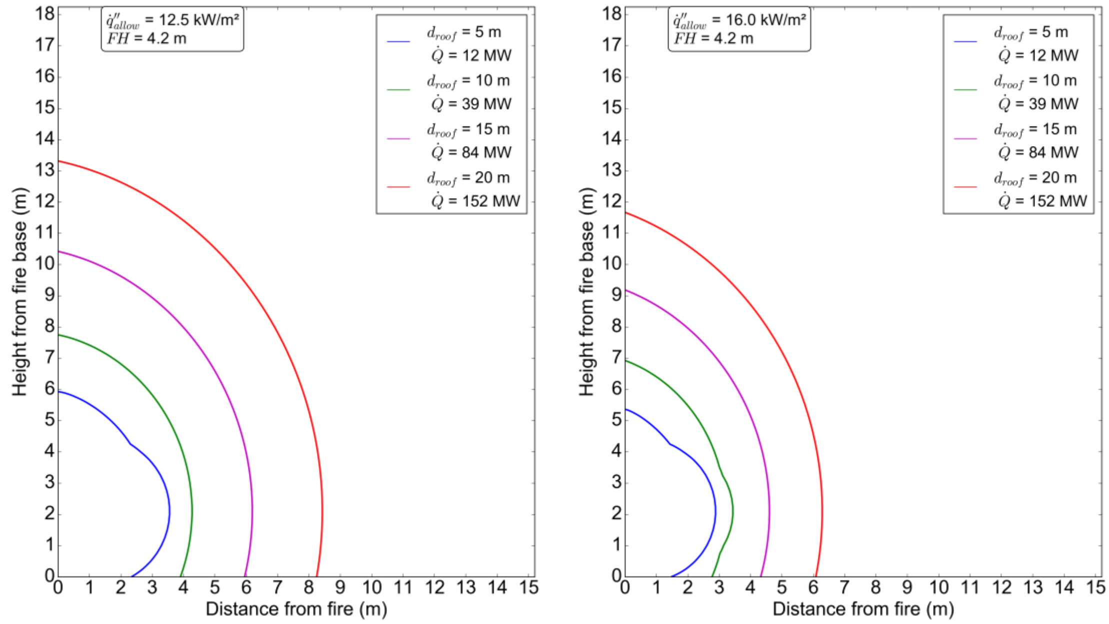


(c) 3 storeys contributing

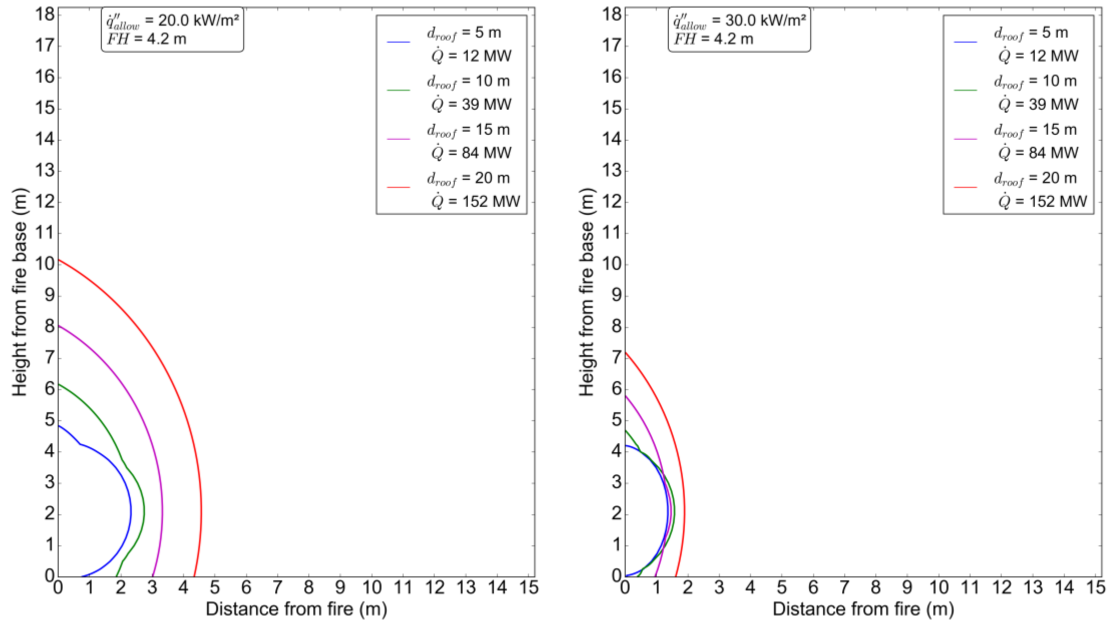


(d) 4 storeys contributing

Figure 44. 16 kW/m² contours with no tilt.



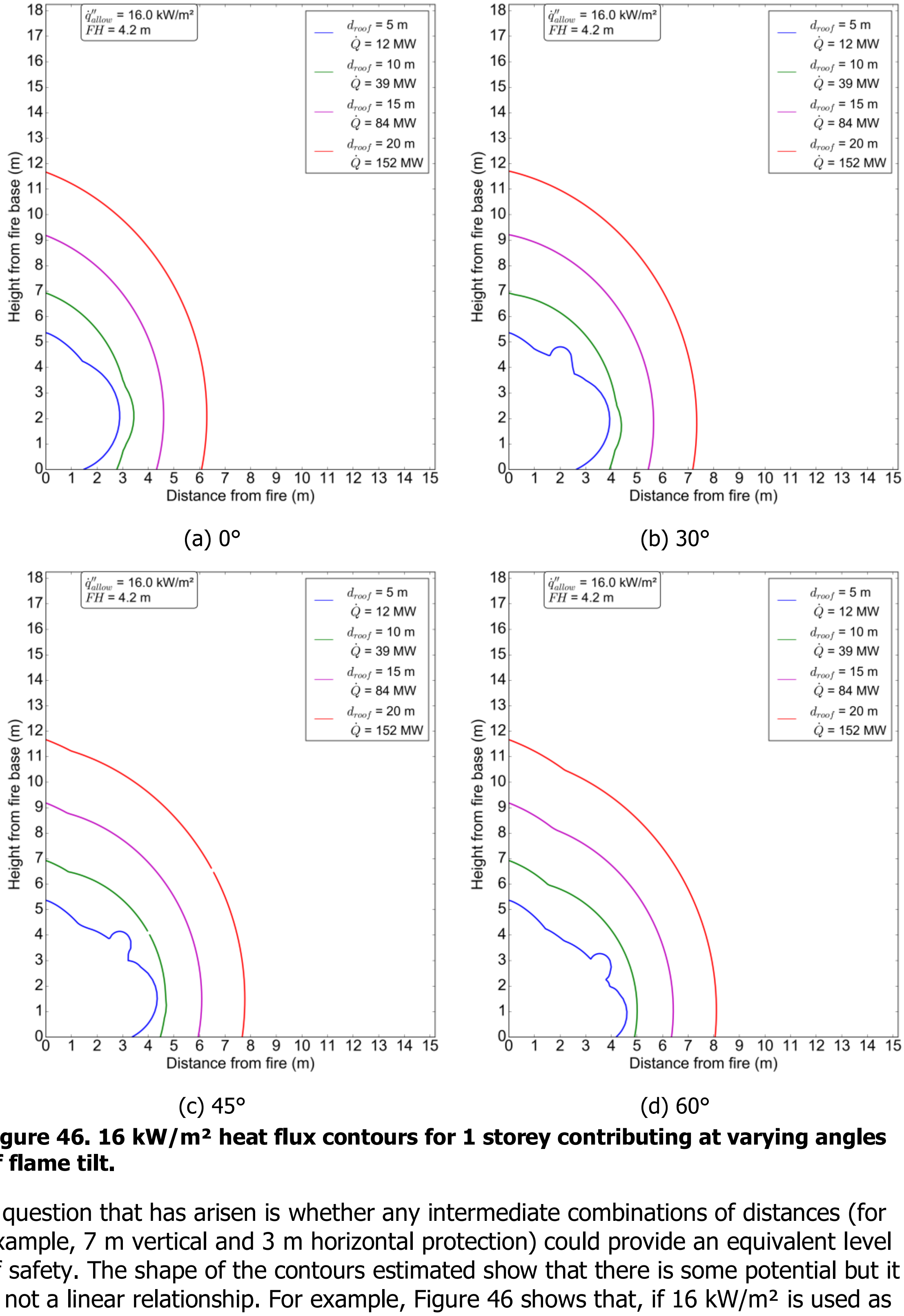
(a) 12.5 kW/m² (b) 16 kW/m²



(c) 20 kW/m² (d) 30 kW/m²

Figure 45. Heat flux contours for 1 storey contributing with no tilt.

The influence of flame tilt on the heat flux contours is shown in Figure 46 for 1 storey contributing. In this case, the maximum heat flux at each point from the vertical flame point source, vertical cylinder, tilted point source and tilted cylinder models is taken. This results in the maximum heights of the heat flux contours adjacent to the fire remaining unchanged in most cases. The horizontal:vertical ratio when wind is present is higher than the current 5 m to 9 m ratio in most cases, indicating that the current requirements do not take wind into account.



(a) 0° (b) 30°

(c) 45° (d) 60°

Figure 46. 16 kW/m² heat flux contours for 1 storey contributing at varying angles of flame tilt.

A question that has arisen is whether any intermediate combinations of distances (for example, 7 m vertical and 3 m horizontal protection) could provide an equivalent level of safety. The shape of the contours estimated show that there is some potential but it is not a linear relationship. For example, Figure 46 shows that, if 16 kW/m² is used as the maximum heat flux criteria for a 15 m square single-storey fire compartment, neglecting wind, a horizontal separation of 4.6 m or vertical protection up to 9.2 m above the roof would be required. A horizontal separation of 1 m would still require approximately 8.5 m of vertical protection or 8 m vertical protection for 2 m separation. At 4 m separation, 5 m of vertical protection would still be required.

Tabulated values for the maximum vertical and horizontal extent of heat flux levels ranging from 12.5 kW/m² to 50 kW/m² are shown in Table 13 to Table 16 for 1–4 storeys contributing, respectively. Percentages are given that compare the tabulated values to the current 9 m vertical to 5 m horizontal requirements.

Table 13. Maximum vertical and horizontal heat flux contour for 1 storey contributing, no tilt.

FH = 3 m/storey x 1.4 storeys flame height (1 storey involved)					
Allowable heat flux (kW/m²)	Protected wall height/horizontal separation	Roof vent size/HRR*			
		5 m 12 MW	10 m 39 MW	15 m 84 MW	20 m 152 MW
12.5	Wall	5.9 / 66%	7.8 / 86%	10.4 / 116%	13.3 / 148%
	Roof	3.6 / 71%	4.3 / 85%	6.2 / 124%	8.4 / 168%
16	Wall	5.4 / 60%	6.9 / 77%	9.2 / 102%	11.7 / 130%
	Roof	2.9 / 58%	3.4 / 69%	4.6 / 92%	6.3 / 126%
20	Wall	4.8 / 54%	6.2 / 69%	8.1 / 90%	10.2 / 113%
	Roof	2.3 / 46%	2.7 / 55%	3.3 / 66%	4.6 / 91%
25	Wall	4.3 / 48%	5.4 / 60%	6.9 / 76%	8.6 / 96%
	Roof	1.8 / 36%	2.1 / 42%	2.2 / 44%	3.0 / 61%
30	Wall	4.2 / 47%	4.7 / 52%	5.8 / 65%	7.2 / 80%
	Roof	1.4 / 27%	1.6 / 31%	1.5 / 29%	1.9 / 38%
50	Wall	4.0 / 45%	0.0 / 0%	0.0 / 0%	0.0 / 0%
	Roof	0.1 / 2%	0.0 / 0%	0.0 / 0%	0.0 / 0%
*Percentages shown relative to 9 m vertical (labelled 'Wall') and 5 m horizontal (labeled ('Roof').					

Table 14. Maximum vertical and horizontal heat flux contour for 2 storeys contributing, no tilt.

FH = 3 m/storey x 1.8 storeys flame height (2 storeys involved)					
Allowable heat flux (kW/m²)	Protected wall height/horizontal separation	Roof vent size/HRR*			
		5 m 16 MW	10 m 46 MW	15 m 96 MW	20 m 170 MW
12.5	Wall	7.1 / 79%	9.0 / 100%	11.7 / 130%	14.6 / 163%
	Roof	4.1 / 82%	5.2 / 103%	7.2 / 143%	9.4 / 189%
16	Wall	6.6 / 73%	8.1 / 90%	10.5 / 116%	13.0 / 144%
	Roof	3.3 / 66%	4.0 / 81%	5.5 / 109%	7.2 / 144%
20	Wall	6.0 / 67%	7.4 / 82%	9.3 / 104%	11.5 / 128%
	Roof	2.6 / 53%	3.2 / 64%	4.1 / 82%	5.4 / 107%
25	Wall	5.5 / 61%	6.6 / 74%	8.2 / 91%	10.0 / 111%
	Roof	2.0 / 40%	2.4 / 49%	2.9 / 57%	3.8 / 75%
30	Wall	5.5 / 61%	6.0 / 67%	7.2 / 80%	8.7 / 96%
	Roof	1.5 / 30%	1.8 / 36%	2.0 / 39%	2.6 / 51%
50	Wall	5.3 / 59%	3.4 / 38%	0.0 / 0%	0.0 / 0%
	Roof	0.5 / 10%	0.1 / 2%	0.0 / 0%	0.0 / 0%
*Percentages shown relative to 9 m vertical (labelled 'Wall') and 5 m horizontal (labeled ('Roof').					

Table 15. Maximum vertical and horizontal heat flux contour for 3 storeys contributing, no tilt.

FH = 3 m/storey x 2.2 storeys flame height (3 storeys involved)									
Allowable heat flux (kW/m²)	Protected wall height/horizontal separation	Roof vent size/HRR*							
		5 m 21 MW		10 m 55 MW		15 m 110 MW		20 m 188 MW	
12.5	Wall	8.3	93%	10.2	113%	13.0	144%	16.0	177%
	Roof	4.5	90%	6.1	121%	8.1	163%	10.5	210%
16	Wall	7.8	86%	9.3	104%	11.7	130%	14.3	159%
	Roof	3.6	73%	4.8	96%	6.3	126%	8.1	162%
20	Wall	7.2	80%	8.6	95%	10.6	118%	12.8	142%
	Roof	2.9	59%	3.8	75%	4.9	97%	6.2	124%
25	Wall	6.7	75%	7.8	87%	9.5	105%	11.3	125%
	Roof	2.4	47%	2.8	57%	3.6	71%	4.5	90%
30	Wall	6.7	74%	7.2	80%	8.5	95%	10.0	111%
	Roof	1.9	39%	2.1	43%	2.6	52%	3.2	64%
50	Wall	6.5	72%	5.2	58%	5.1	56%	5.1	56%
	Roof	0.9	19%	0.5	11%	0.3	6%	0.2	5%

*Percentages shown relative to 9 m vertical (labelled 'Wall') and 5 m horizontal (labeled ('Roof').

Table 16. Maximum vertical and horizontal heat flux contour for 4 storeys contributing, no tilt.

FH = 3 m/storey x 2.6 storeys flame height (4 storeys involved)									
Allowable heat flux (kW/m²)	Protected wall height/horizontal separation	Roof vent size/HRR*							
		5 m 27 MW		10 m 65 MW		15 m 124 MW		20 m 208 MW	
12.5	Wall	9.5	106%	11.3	126%	14.2	158%	17.2	192%
	Roof	5.2	104%	7.0	140%	9.1	182%	11.5	230%
16	Wall	9.0	100%	10.5	116%	12.9	144%	15.5	173%
	Roof	4.3	86%	5.6	112%	7.2	144%	9.0	180%
20	Wall	8.4	94%	9.7	108%	11.8	131%	14.1	156%
	Roof	3.6	72%	4.5	90%	5.6	113%	7.0	140%
25	Wall	8.0	89%	9.0	100%	10.7	119%	12.6	140%
	Roof	2.9	59%	3.5	70%	4.3	85%	5.2	104%
30	Wall	7.9	88%	8.4	93%	9.8	109%	11.3	126%
	Roof	2.5	49%	2.7	55%	3.2	65%	3.9	78%
50	Wall	7.8	86%	6.5	72%	6.8	75%	7.1	79%
	Roof	1.4	27%	1.0	20%	0.8	16%	0.8	15%

*Percentages shown relative to 9 m vertical (labelled 'Wall') and 5 m horizontal (labeled ('Roof').

Another comparison can be made to the Australian requirements of 6 m vertical protection or 3 m horizontal separation using 20 kW/m² as a comparison, which relates to the Australian Verification Method CV1 and CV2 requirements for buildings to not cause or withstand 20 kW/m² 3 m from a boundary (on adjacent allotments) or 6 m from a boundary (on the same allotment). A vertical flame from a 10 m square opening with 1 storey involved is estimated to cause 20 kW/m² at 6.2 m vertically or 2.7 m horizontally.

The influence of a 45° flame tilt on the horizontal separation can be seen in Table 17 to Table 20. The tilt has more influence on the horizontal extent because the vertical flame radiation models are included, and the required protected wall height only increased up to 10% for heat fluxes up to 30 kW/m². Flame tilt is estimated to be more influential for taller, smaller area fires at high heat fluxes. The estimated 45° tilted flame envelope is comparable to the NFPA 80A requirements if 12.5 kW/m² is used as the criteria with 10 m to 15 m square compartments. While the horizontal envelope is typically lower than the NFPA 80A requirement, greater tilt angles are possible at moderate wind speeds.

Table 17. Maximum vertical and horizontal heat flux contour for 1 storey contributing, 45° tilt.

FH = 3 m/storey x 1.4 storeys flame height (1 storey involved)									
Allowable heat flux (kW/m²)	Horizontal separation	Roof vent size/HRR							
		5 m		10 m		15 m		20 m	
		12 MW		39 MW		84 MW		152 MW	
12.5	No tilt / 45° tilt	3.6 /	4.9	4.3 /	5.8	6.2 /	7.7	8.4 /	9.9
	% increase / % relative to 5 m	38%	98%	35%	115%	24%	154%	18%	198%
16	No tilt / 45° tilt	2.9 /	4.3	3.4 /	4.7	4.6 /	6.1	6.3 /	7.8
	% increase / % relative to 5 m	51%	87%	37%	94%	32%	122%	24%	155%
20	No tilt / 45° tilt	2.3 /	3.9	2.7 /	4.1	3.3 /	4.8	4.6 /	6.1
	% increase / % relative to 5 m	69%	78%	51%	83%	45%	96%	33%	121%
25	No tilt / 45° tilt	1.8 /	3.5	2.1 /	3.6	2.2 /	3.7	3.0 /	4.5
	% increase / % relative to 5 m	98%	71%	74%	73%	68%	73%	49%	90%
30	No tilt / 45° tilt	1.4 /	3.3	1.6 /	3.3	1.5 /	3.2	1.9 /	3.4
	% increase / % relative to 5 m	141%	66%	109%	66%	117%	63%	78%	68%
50	No tilt / 45° tilt	0.1 /	2.7	0.0 /	1.1	0.0 /	0.8	0.0 /	0.7
	% increase / % relative to 5 m	2124%	54%	N/A	22%	N/A	17%	N/A	14%

Table 18. Maximum vertical and horizontal heat flux contour for 2 storeys contributing, 45° tilt.

FH = 3 m/storey x 1.8 storeys flame height (2 storeys involved)									
Allowable heat flux (kW/m²)	Protected wall height/horizontal separation	Roof vent size/HRR							
		5 m		10 m		15 m		20 m	
		16 MW		46 MW		96 MW		170 MW	
12.5	No tilt / 45° tilt	4.1 /	5.9	5.2 /	7.1	7.2 /	9.1	9.4 /	11.4
	% increase / % relative to 5 m	45%	118%	37%	141%	27%	181%	20%	227%
16	No tilt / 45° tilt	3.3 /	5.3	4.0 /	5.9	5.5 /	7.4	7.2 /	9.1
	% increase / % relative to 5 m	61%	106%	46%	118%	35%	147%	27%	182%
20	No tilt / 45° tilt	2.6 /	4.8	3.2 /	5.1	4.1 /	6.0	5.4 /	7.3
	% increase / % relative to 5 m	83%	97%	59%	103%	47%	120%	36%	146%
25	No tilt / 45° tilt	2.0 /	4.4	2.4 /	4.6	2.9 /	4.8	3.8 /	5.7
	% increase / % relative to 5 m	120%	88%	86%	91%	67%	95%	51%	113%
30	No tilt / 45° tilt	1.5 /	4.1	1.8 /	4.2	2.0 /	4.0	2.6 /	4.5
	% increase / % relative to 5 m	176%	83%	129%	83%	106%	81%	75%	89%
50	No tilt / 45° tilt	0.5 /	3.7	0.1 /	2.0	0.0 /	1.7	0.0 /	1.6
	% increase / % relative to 5 m	612%	74%	N/A	40%	N/A	35%	N/A	33%

Table 19. Maximum vertical and horizontal heat flux contour for 3 storeys contributing, 45° tilt.

FH = 3 m/storey x 2.2 storeys flame height (3 storeys involved)									
Allowable heat flux (kW/m^2)	Protected wall height/horizontal separation	Roof vent size/HRR							
		5 m		10 m		15 m		20 m	
		21 MW		55 MW		110 MW		188 MW	
12.5	No tilt / 45° tilt	4.5 /	6.9	6.1 /	8.4	8.1 /	10.5	10.5 /	12.8
	% increase / % relative to 5 m	53%	138%	38%	168%	29%	209%	22%	256%
16	No tilt / 45° tilt	3.6 /	6.2	4.8 /	7.1	6.3 /	8.6	8.1 /	10.4
	% increase / % relative to 5 m	72%	125%	49%	142%	37%	173%	29%	209%
20	No tilt / 45° tilt	2.9 /	5.7	3.8 /	6.1	4.9 /	7.2	6.2 /	8.5
	% increase / % relative to 5 m	96%	114%	62%	122%	48%	144%	38%	170%
25	No tilt / 45° tilt	2.4 /	5.3	2.8 /	5.5	3.6 /	5.9	4.5 /	6.8
	% increase / % relative to 5 m	125%	106%	93%	109%	66%	118%	52%	136%
30	No tilt / 45° tilt	1.9 /	5.0	2.1 /	5.0	2.6 /	4.9	3.2 /	5.6
	% increase / % relative to 5 m	159%	100%	134%	100%	90%	98%	73%	111%
50	No tilt / 45° tilt	0.9 /	4.5	0.5 /	2.9	0.3 /	2.6	0.2 /	2.6
	% increase / % relative to 5 m	378%	89%	N/A	57%	N/A	53%	N/A	51%

Table 20. Maximum vertical and horizontal heat flux contour for 4 storeys contributing, 45° tilt.

FH = 3 m/storey x 2.6 storeys flame height (4 storeys involved)									
Allowable heat flux (kW/m^2)	Protected wall height/horizontal separation	Roof vent size/HRR							
		5 m		10 m		15 m		20 m	
		27 MW		65 MW		124 MW		208 MW	
12.5	No tilt / 45° tilt	5.2 /	8.0	7.0 /	9.8	9.1 /	11.9	11.5 /	14.3
	% increase / % relative to 5 m	53%	159%	39%	195%	30%	238%	24%	286%
16	No tilt / 45° tilt	4.3 /	7.1	5.6 /	8.4	7.2 /	9.9	9.0 /	11.8
	% increase / % relative to 5 m	66%	143%	49%	167%	38%	199%	31%	236%
20	No tilt / 45° tilt	3.6 /	6.6	4.5 /	7.2	5.6 /	8.4	7.0 /	9.8
	% increase / % relative to 5 m	84%	132%	62%	145%	49%	168%	39%	195%
25	No tilt / 45° tilt	2.9 /	6.1	3.5 /	6.3	4.3 /	7.0	5.2 /	8.0
	% increase / % relative to 5 m	108%	123%	82%	127%	65%	140%	53%	159%
30	No tilt / 45° tilt	2.5 /	5.8	2.7 /	5.9	3.2 /	6.0	3.9 /	6.6
	% increase / % relative to 5 m	136%	117%	115%	118%	85%	120%	71%	133%
50	No tilt / 45° tilt	1.4 /	5.5	1.0 /	3.8	0.8 /	3.6	0.8 /	3.5
	% increase / % relative to 5 m	304%	109%	N/A	75%	N/A	71%	N/A	70%

6.4 Fire duration, fire loading, and fire brigade response

With the previously developed peak HRR from flame heights, an estimate of fire duration can be made based on assumptions of the fire HRR time history and fire load. It should be noted that, in reality, the duration will depend on the time it will take for the roof to be compromised, available ventilation prior to roof collapse, the contribution of combustible building elements to the fire load and the actual growth and decay of the fire. In general, most of these factors should decrease the actual duration of heat on the exposed higher wall with the exception of additional fire load contributions. Lower peak HRRs could correspond to longer durations as well.

Assuming an FLED of 400 MJ/m² based on the C/VM2 prescription for residential and office occupancies (multiplied by the number of storeys burning) and a fast t² fire up to the peak HRR based on the flame height with no decay gives the estimated maximum fire durations listed in Table 21. Flame heights are estimated assuming a square compartment. Durations for 800 MJ/m² or 1200 MJ/m² fire loads can be calculated by multiplying by two or three, respectively.

Table 21. Estimated maximum fire duration at peak HRR (FLED = 400 MJ/m², fast t² growth to peak HRR, no decay).

Storeys burning / Area of compartment (m²)	1	2	3	4
	Peak HRR (MW)/Fire duration (minutes)			
25	12 / 11	16 / 17	21 / 20	27 / 21
100	39 / 12	46 / 23	55 / 30	65 / 35
225	84 / 10	96 / 23	110 / 33	124 / 39
400	152 / 7	170 / 21	188 / 31	208 / 40

These times and/or the expected heat flux could be modified based on fire brigade response. Access for firefighting activities to the roof and/or an adjacent wall should be considered. If there is less than 5 m separation between the wall and lower roof, access is likely to be restricted and an aerial appliance may be required. Since not all stations have aerial appliances, extra response time should be considered. Also, suitable set-up locations should be included in the design. Measured set-up times for FENZ aerial appliances range from 160 s to 420 s, and additional time is required to position and charge the monitor (Claridge, 2010).

The probability of full roof collapse and complete compartment involvement is not known.

6.5 Summary

This section has applied the models described in section 3 to hypothetical building geometries as a comparison to prescriptive regulatory requirements. The "9 or 5" rule has been shown to roughly compare to the estimated 16 kW/m² heat flux envelope created by flames venting from a 10 × 10 m roof with 1 storey contributing to the flames and no flame tilt. When flame tilt is taken into consideration, the 5 m horizontal separation becomes tenuous. The envelope may be scaled up or down depending on the potential size of the roof opening (i.e. the unprotected area of the roof) and the number of storeys contributing to the fire. However, note that this section does not constitute validation at this scale but is only a hypothetical comparison to the prescriptive regulatory requirements.

7. Conclusions and recommendations

7.1 Conclusions

This study report has provided information on the historical implementation of fire spread from lower roofs in the New Zealand building regulations, provided comparisons to requirements in other countries and demonstrated how existing fire engineering knowledge can be applied to create an estimate of the potential heat flux envelope that may affect a higher external wall if fire breaches a lower adjacent roof. The origins of the New Zealand requirements can be traced back to DZ 4226:1984, which included a "10 to 6" rule rather than a "9 or 5" rule (described in section 2.2.1). DZ 4226:1984 indicates that this requirement was derived from NFPA 80A, which includes a range of requirements depending on the number of storeys contributing to the fire and is more onerous than the New Zealand Acceptable Solutions for all cases other than 1 storey contributing.

Other jurisdictions such as Australia, the UK, the US, Canada and Sweden all include fire spread from lower roofs requirements but all are slightly different. Also, the context of the general roof and wall requirements must be taken into consideration. New Zealand has the most onerous specific fire spread from lower roofs requirements. However, in general, non-combustible and fire-rated construction is required in more instances in most other jurisdictions. This means that the mechanism of fire spread from lower roofs is covered in many instances by the general construction requirements. Allowable unprotected openings are also greater in New Zealand than in the US and Canada. Canada, the US and the UK include external flame spread testing requirements for roofs, which may influence how quickly a fire can spread through a roof.

This report has discussed the validity of flame height and heat flux correlations for this particular scenario as evaluated against small-scale experiments. While there is substantial scatter in the comparisons, they do appear to provide a reasonable approach to estimating the heat flux on walls from fires emanating from adjacent lower roofs. In general, the NRL/HAI correlation appears to be best suited to evaluating heat fluxes on a wall with a fire source directly adjacent up to the tip of the flame. The point source and vertical cylinder models are better suited for determining envelopes at typical minimum ignition heat flux levels (12–30 kW/m²).

The potential heat flux envelopes have been demonstrated using estimated maximum flame heights, flame height correlations and point source and cylindrical flame radiation models. Comparisons to the New Zealand Acceptable Solutions, NFPA 80A and Australian requirements have shown that all can be shown to be reasonable for certain compartment sizes and heat flux criteria. The New Zealand and Australian requirements are in line with estimates of heat flux from vertical flames using their respective heat flux criteria. NFPA 80A covers the tilted flame scenario as well. The potential effects of fire compartment size and number of floors have been shown.

7.2 Recommendations

The NZBC performance criteria do not provide quantitative targets specifically for this application (as linked in the C/VM2 vertical fire spread scenario). This should be addressed for both fire spread from lower roofs and fires spreading vertically through unprotected openings. As an alternative for this report, the 16 kW/m² horizontal fire spread scenario performance criterion has been used.

Based on the information presented in this report, the 9 m wall vertical protection or 5 m roof protection/horizontal separation in the current New Zealand Acceptable Solutions along with the 16 kW/m² heat flux criteria do not seem overly conservative in all situations. Any changes to these requirements should include analysis of the context of the general roof and wall fire protection requirements.

The use of a single requirement for all compartment configurations may be overly simplistic and does not adequately reflect the potential risk for the range of geometries that would be expected in typical building configurations. There are situations for the compartment under the lower roof, particularly for smaller single-storey configurations, where reducing the requirements may be justified. At the opposite end of the spectrum, additional horizontal separation distance may be warranted if the building geometry would result in prevailing winds tilting a flame from a roof over a large multi-storey fire compartment in the direction of a higher external wall. Requiring ignition-resistant external wall materials (such as the 30 kW/m² boundary radiation limit and options for material ignitability within 1 m of the boundary in clauses C3.6 and C3.7 in conjunction with fire-resistant glazed openings) with wall fire resistance ratings that are based on the expected incident heat flux would appear to be more justifiable than fire resistance rating requirements alone. Since the requirement here is for fire spread from roofs, not fire spread to roofs, fire rating from the outside in would only be required. Typically only -/30/30 would be required based on the expected heat flux, but specific analysis should be used to verify for individual circumstances.

Further work is necessary to investigate the validity of the flame height, tilt and radiation correlations used in this analysis at larger scales. A combination of intermediate and full- scale experiments and modelling would be required to provide robust recommendations and/or refined correlations. Extending the methodology to non-square roof vents would be useful.

Further investigation of actual fire incident data has the potential to improve understanding of the risk of a fire spread from lower roof scenario with typical building geometry configurations in New Zealand. This work would revisit and update the 1960s NFPA data on flame heights from buildings and investigate the probability of full roof collapse and total compartment involvement with the current New Zealand building stock.

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Appendix A: Related general external fire spread prescriptive requirements

A.1 New Zealand

A.1.1 C/ASx

Section 2.3 in C/ASx lists the fire resistance ratings for the relevant risk group. Paragraphs 2.3.8 and 2.3.9 are relevant for external walls and read as follows:

> 2.3.8 Except as required by Paragraph 2.3.9, areas of external wall not permitted to be unprotected areas shall be rated for fire exposure from within a firecell.
>
> 2.3.9 Areas of external wall not permitted to be unprotected areas shall be rated for fire exposure from both sides equally where:
> (a) Walls are within 1.0 m of the relevant boundary, or
> (b) The building height is more than 10 m, or
> (c) The final exit is two or more floor levels below any risk group SM occupancy.

The C/ASx commentary notes that the requirement for rating on both sides equally in paragraph 2.3.9 "recognizes that, where the wall is closer than 1.0 m to the boundary, there is a responsibility for the wall to add to the protection of the building from any fire on the other side of the boundary".

A.1.2 Fire resistance rating test methods

Appendix C5.1.1 of C/AS2 describes the test method prescribed for assigning fire resistance ratings to primary and secondary elements, closures and fire stops as AS 1530.4:2014 or NZS/BS 476:1987 Parts 21 and 22.

AS 1530.4:2014 section 4 describes testing requirements for horizontal separating elements including floors, roofs, and ceilings. The thermal conditions are "heating from the underside".

NZS/BS 476-21:1987 section 7 describes the determination of the fire resistance of loadbearing floors and flat roofs up to 10° pitch and states that the test evaluates the ability of the roof to "withstand exposure to fire from their undersides".

A.1.3 Allowable unprotected areas

The C/ASx commentary for section 5.2 indicates that the Acceptable Solutions mitigate horizontal fire spread across a boundary by "restricting the radiation that might be incident to property on the other side of the boundary". This is achieved by prescribing three factors:

- Distance to the boundary.
- Amount of wall area that could radiate heat.
- Sprinkler protection.

Based on the distance to the boundary and whether sprinklers are present or not, there are varying amounts of the wall that are allowed to be unprotected or fire resistance rated glazing. The following is an example from C/AS2.

5.2.4 If a wall or part of a wall is less than 1.0 m from the relevant boundary, a combination of small unprotected areas and fire resisting glazing is permitted as detailed in Paragraph 5.4.

5.2.5 Table 5.2 applies only to the permitted unprotected area in external walls 1.0 m or more from the relevant boundary. This can be combined with the areas of fire resisting glazing and small unprotected areas in Paragraph 5.4.

5.2.6 Regardless of the method adopted, all parts of an external wall other than allowable unprotected areas shall have the appropriate FRR as specified by the relevant parts of this Acceptable Solution.

5.4 Small openings and fire resisting glazing

5.4.1 External wall construction shall meet the following requirements:
(a) Unprotected areas (referred to as Type A areas) and areas of fire resisting glazing (referred to as Type B areas) shall be located to comply with Figure 5.1, and
(b) The remainder of the wall shall be fire rated equally for exposure to fire on both sides.

Size and spacing of Type A and Type B areas

5.4.2 Type A areas shall be no greater than 0.1 m². Type B areas shall be no greater than permitted by Table 5.1 according to the distance from the relevant boundary.

5.4.3 The fire resisting glazing shall be rated for integrity and the FRR of both the glazing and the external wall shall be in accordance with Paragraph 2.3.

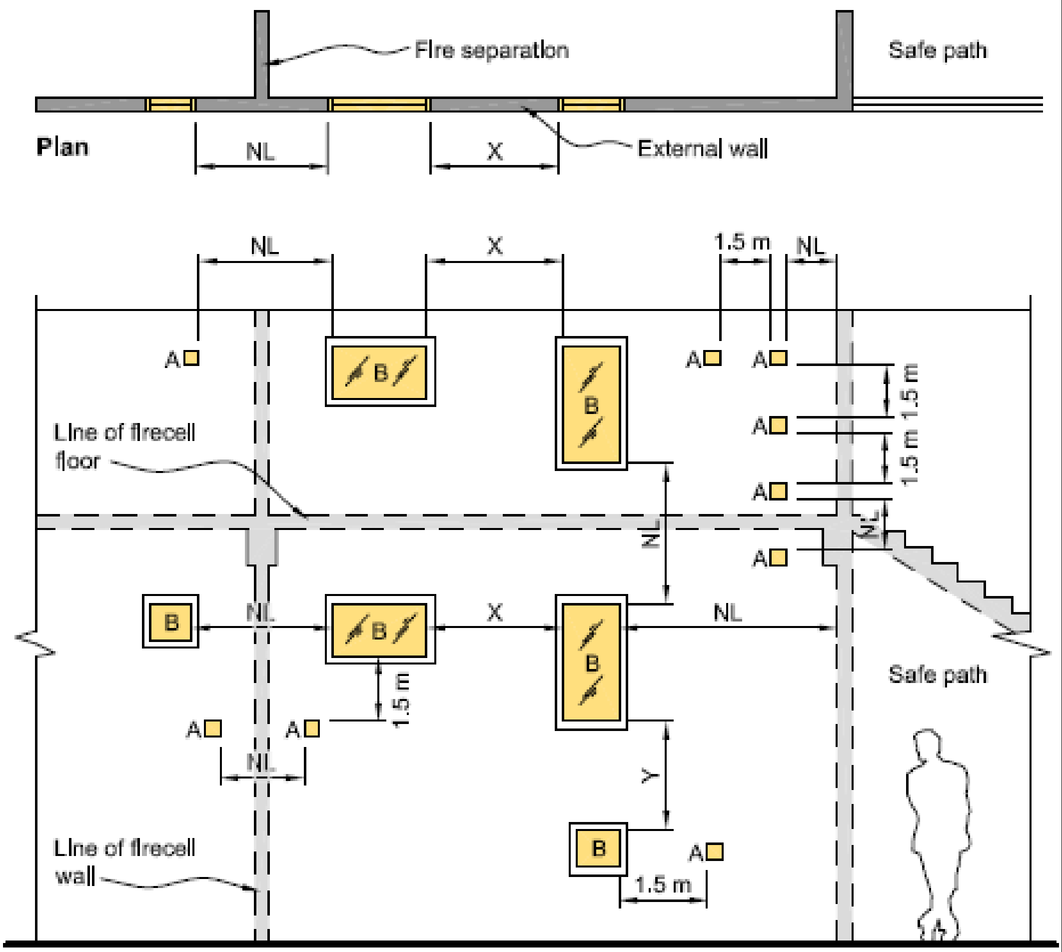
Table 22. Table 5.1 from C/AS2.

Table 5.1 Permitted areas of fire resisting glazing in unsprinklered firecells

Distance to *relevant boundary* (m)	Glazing area (m²)
0.0	1.0
0.5	1.5
0.6	2.0
0.7	3.0
0.8	3.5
0.9	5.0
1.0	6.0
1.1	7.5
1.2	8.5
1.3	10.0
1.4	12.0
1.5	13.0
1.6	14.0
1.7	15.0
>1.7	Unlimited

Note: Sprinklered *firecells* have no limit on the area of *fire resisting glazing* allowed.

Figure 5.1 **Method 1 – Permitted small unprotected areas and fire resisting glazing**
Paragraphs 5.4.1 and 5.4.4



Elevation

Dimensions shown are minimum distances between Type A unprotected areas and of Type B fire resisting glazing

Legend

A☐ Type A *unprotected areas* of 0.1 m² maximum

B Type B areas of *fire resisting glazing* complying with Table 5.1

NL No limitation on spacing

X Spacing to be no less than the greater of the widths of the two Type B areas being considered

Y Spacing to be no less than the greater of the heights of the two Type B areas being considered

Figure 47. C/AS2 Figure 5.1.

C/AS2 Tables 5.2 and 5.3 provide the information required to meet the maximum unprotected area criteria in section 5.5 of C/AS2. Similar tables are provided in the other C/ASx Acceptable Solutions.

Table 23. C/AS2 Tables 5.2 and 5.3.

Errata 1 Feb 2013

Table 5.2 Maximum percentage of unprotected area for external walls

	Risk group SM	Percentage of wall area allowed to be unprotected											
		Column 2		Column 3		Column 4		Column 5		Column 6		Column 7	
Errata 1 Feb 2013	Minimum distance to *relevant boundary* (m) (see Figure 5.3)	Angle between wall and *relevant boundary* up to 45°				Angle between wall and *relevant boundary* 46° to 60°				Angle between wall and *relevant boundary* 61° to 89°			
		Width of unsprinklered *firecell*		Width of sprinklered *firecell*		Width of unsprinklered *firecell*		Width of sprinklered *firecell*		Width of unsprinklered *firecell*		Width of sprinklered *firecell*	
		Up to 5 m	Greater than 5 m	Up to 5 m	Greater than 5 m	Up to 5 m	Greater than 5 m	Up to 5 m	Greater than 5 m	Up to 5 m	Greater than 5 m	Up to 5 m	Greater than 5 m
Errata 1 Feb 2013	Less than 1	0	0	0	0	0	0	0	0	0	0	0	0
	1	35	30	70	60	45	33	90	66	55	35	100	70
	2	55	40	100	80	70	45	100	90	85	55	100	100
	3	80	55	100	100	95	65		100	100	80		100
	4	100	70			100	90				100		
	5		90				100						
	6		100										

Table 5.3 Maximum size of largest permitted single unprotected area in external walls

	Unsprinklered *firecell*		Sprinklered *firecell*	
Minimum distance to *relevant boundary* (m) (see Figure 5.3)	Maximum largest single *unprotected area* (m²)	Minimum distance to adjacent *unprotected areas* (m)	Maximum largest single *unprotected area* (m²)	Minimum distance to adjacent *unprotected areas* (m)
1	1	1	15	1.5
2	6	1.5	35	2.5
3	13	4.5	60	3.5
4	20	5.5	96	4
5	29	6.5	139	4.5
6	40	7.5	No requirement	No requirement

A.2 Australia

A.2.1 Part Two (Class 1 residential buildings)

External walls of Class 1 residential buildings are required to have an FRR (the term FRL or fire-resistance level is used in Australia) of 60/60/60 if they are within 900 mm of an allotment boundary (other than adjoining road alignments or other public spaces) or 1.8 m of another building on the same allotment. Openings in external walls required to be fire resisting must be protected by either non-openable fire windows with an FRR of -/60/- or self-closing solid-core doors not less than 35 mm thick, excluding subfloor and roof vents, weepholes, control joints, construction joints and penetrations for pipes or conduit. There are also concessions for small windows in non-habitable rooms (such as bathrooms).

A.2.2 Part One (Class 2 and 3 residential buildings)

Table C1.1 of Part C1 states that Class 2 and 3 buildings require Type A construction if their height is 3 or more storeys, Type B construction for 2 storeys and Type C construction for 1 storey, except for as allowed in section C1.5. Section C1.5 allows 2-storey Class 2 buildings if each sole occupancy unit has

(i) access to at least 2 exits; or

(ii) its own direct access to a road or open space.

In Specification C1.1-3, Type A Fire-Resisting Construction, the required fire resistance rating for external walls and roofs are listed in Table 24.

Table 24. National Construction Code of Australia Specification C1.1 Table 3.

Building element	Class of building — FRL: (in minutes) *Structural adequacy/Integrity/Insulation*			
	2, 3 or 4 part	5, 7a or 9	6	7b or 8
EXTERNAL WALL (including any column and other building element incorporated therein) or other external building element, where the distance from any *fire-source feature* to which it is exposed is—				
For *loadbearing* parts—				
less than 1.5 m	90/ 90/ 90	120/120/120	180/180/180	240/240/240
1.5 to less than 3 m	90/ 60/ 60	120/ 90/ 90	180/180/120	240/240/180
3 m or more	90/ 60/ 30	120/ 60/ 30	180/120/ 90	240/180/ 90
For non-*loadbearing* parts—				
less than 1.5 m	–/ 90/ 90	–/120/120	–/180/180	–/240/240
1.5 to less than 3 m	–/ 60/ 60	–/ 90/ 90	–/180/120	–/240/180
3 m or more	–/–/–	–/–/–	–/–/–	–/–/–
ROOFS	90/ 60/ 30	120/ 60/ 30	180/ 60/ 30	240/ 90/ 60

The term 'fire-source feature' in Table 10 is defined as:

(a) the far boundary of a road, river, lake or the like adjoining the allotment; or

(b) a side or rear boundary of the allotment; or

(c) an external wall of another building on the allotment which is not a Class 10 building.

The term 'building element' in Table 10 (or part of) is deemed to be exposed to a fire source feature if:

> any of the horizontal straight lines between that part and the fire-source feature, or vertical projection of the feature, is not obstructed by another part of the building that—

(i) has a FRL of not less than 30/-/-; and

(ii) is neither transparent or translucent.

Exclusions include exposures to fire source features that are:

(i) an external wall of another building that stands on the allotment and the part concerned is more than 15 m above the highest part of the external wall; or

(ii) a side or rear boundary of the allotment and the part concerned is below the level of the finished ground at every relevant part of the boundary concerned.

Section 3.5 lists concessions for roofs:

A roof need not comply with Table 3 if its covering is non-combustible and the building—

(a) has a sprinkler system complying with Specification E1.5 is installed throughout; or

(b) has a rise in storeys of 3 or less; or

(c) is of Class 2 or 3; or

(d) has an effective height of not more than 25 m and the ceiling immediately below the roof has a **resistance to the incipient spread of fire** to the roof space of not less than 60 minutes.

Section 3.6 lists concessions for rooflights:

If a roof is required to have an FRL or its covering is required to be non-combustible, rooflights or the like installed in that roof must-

(a) have an aggregate area of not more than 20% of the roof surface; and

(b) be not less than 3 m from-

  (i) any boundary of the allotment other than the boundary with a road or public place; and

  (ii) any part of the building which projects above the roof unless that part has the FRL required of a fire wall and any openings in that part of the wall for 6 m vertically above the rooflight or the like are protected in accordance with C3.4; and

  (iii) any rooflight or the like in an adjoining sole-occupancy unit if the walls bounding the unit are required to have an FRL; and

  (iv) any rooflight or the like in an adjoining fire-separated section of the building; and

(c) if the ceiling with a resistance to the incipient spread of fire is required, be installed in a way that will maintain the level of protection provided by the ceiling to the roof space.

In Specification C1.1-4, Type B Fire-Resisting Construction, the required fire resistance ratings for external walls are included in Table 4 (Table 25). Roofs do not have fire resistance requirements for Type B construction.

External walls for both Type A and Type B construction must be non-combustible, as determined by testing to AS 1530.1. In Specification C1.1-5, Type C Fire-Resisting Construction, the only fire resistance rating requirement for external walls is 90/90/90 when exposed to a fire-source feature within 1.5 m. Roofs are not required to be fire-rated.

Specification C3.2 discusses the protection of external wall openings:

> (a) if the distance between the opening and the fire-source feature to which it is exposed is less than –
>
> (i) 3 m from a side or rear boundary of the allotment; or
>
> (ii) 6 m from the far boundary of a road, river, lake, or the like adjoining the allotment, if not located in a storey at or near ground level; or
>
> (iii) 6 m from another building on the allotment that is not Class 10,
>
> be protected in accordance with C3.4 and if wall-wetting sprinklers are used, they are located externally;

Specification C3.4 (a)(ii) lists requirements for windows as --/60/-- automatic closing shutters or fire windows (can also be permanently fixed closed) or wall-wetting sprinklers with windows that are automatically closing or permanently fixed closed.

Table 25. National Construction Code of Australia Specification C1.1 Table 4.

Table 4 TYPE B CONSTRUCTION: FRL OF BUILDING ELEMENTS

Building element	**Class of building—FRL: (in minutes)** *Structural adequacy/Integrity/Insulation*			
	2, 3 or 4 part	**5, 7a or 9**	**6**	**7b or 8**
EXTERNAL WALL (including any column and other building element incorporated therein) or other external building element, where the distance from any *fire-source feature* to which it is exposed is—				
For *loadbearing* parts—				
less than 1.5 m	90/ 90/ 90	120/120/120	180/180/180	240/240/240
1.5 to less than 3 m	90/ 60/ 30	120/ 90/ 60	180/120/ 90	240/180/120
3 to less than 9 m	90/ 30/ 30	120/ 30/ 30	180/ 90/ 60	240/ 90/ 60
9 to less than 18 m	90/ 30/–	120/ 30/–	180/ 60/–	240/ 60/–
18 m or more	–/–/–	–/–/–	–/–/–	–/–/–
For non-*loadbearing* parts—				
less than 1.5 m	–/ 90/ 90	–/120/120	–/180/180	–/240/240
1.5 to less than 3 m	–/ 60/ 30	–/ 90/ 60	–/120/ 90	–/180/120
3 m or more	–/–/–	–/–/–	–/–/–	–/–/–

Section C3.3 lists the requirements for external walls and associated openings. Unless the walls each have a fire resistance rating of 60/60/60 and the openings are protected in accordance with C3.4, the distance between external walls and associated openings must be as listed in Table C3.3 (Table 26).

Table 26. National Construction Code of Australia Table C3.3.

Table C3.3 DISTANCE BETWEEN EXTERNAL WALLS AND ASSOCIATED OPENINGS IN DIFFERENT FIRE COMPARTMENTS

Angle between walls	Min. Distance
0° (walls opposite)	6 m
more than 0° to 45°	5 m
more than 45° to 90°	4 m
more than 90° to 135°	3 m
more than 135° to less than 180°	2 m
180° or more	Nil

A.3 Canada

The NBCC has the following relevant general prescriptive requirements. Allowable areas of unprotected openings are given in Table 27, Table 28 and Table 29, and required fire resistance ratings for external walls are given in Table 30. Occupancy group classifications are shown in Table 31.

Table 27. National Building Code of Canada 2015 Table 3.2.3.1.A.

Table 3.2.3.1.A.
Maximum Concentrated Area of Unprotected Openings
Forming Part of Sentence 3.2.3.1.(5)

Limiting Distance, m	Maximum Area of Individual *Unprotected Openings*, m^2
Less than 1.2	0
1.2	0.35
1.5	0.78
2.0	1.88

Table 28. National Building Code of Canada 2015 Table 3.2.3.1.B.

Table 3.2.3.1.B.
Unprotected Opening Limits for a Building or Fire Compartment that is not Sprinklered Throughout
Forming Part of Article 3.2.3.1.

Exposing Building Face		Area of *Unprotected Opening* for Groups A, D, and F, Division 3 *Occupancies*, %																									
Max. Area, m^2	Ratio (L/H or H/L)[1]	*Limiting Distance*, m																									
		0	1.2	1.5	2.0	2.5	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	25	30	35	40	45	50
	Less than 3 : 1	0	8	10	18	29	46	91	100																		
10	3 : 1 to 10 : 1	0	8	12	21	33	50	96	100																		
	over 10 : 1	0	11	18	32	48	68	100																			
	Less than 3 : 1	0	7	9	14	22	33	63	100																		
15	3 : 1 to 10 : 1	0	8	10	17	25	37	67	100																		
	over 10 : 1	0	10	15	26	39	53	87	100																		
	Less than 3 : 1	0	7	9	12	18	26	49	81	100																	
20	3 : 1 to 10 : 1	0	8	10	15	21	30	53	85	100																	
	over 10 : 1	0	9	14	23	33	45	72	100																		
	Less than 3 : 1	0	7	8	11	16	23	41	66	98	100																
25	3 : 1 to 10 : 1	0	8	9	13	19	26	45	70	100																	
	over 10 : 1	0	9	13	21	30	39	62	90	100																	
	Less than 3 : 1	0	7	8	11	15	20	35	56	83	100																
30	3 : 1 to 10 : 1	0	7	9	12	17	23	39	61	88	100																
	over 10 : 1	0	8	12	19	27	36	56	79	100																	
	Less than 3 : 1	0	7	8	10	13	17	28	44	64	89	100															
40	3 : 1 to 10 : 1	0	7	8	11	15	20	32	48	69	93	100															
	over 10 : 1	0	8	11	17	24	31	47	66	88	100																
	Less than 3 : 1	0	7	8	9	12	15	24	37	53	72	96	100														
50	3 : 1 to 10 : 1	0	7	8	10	14	18	28	41	57	77	100															
	over 10 : 1	0	8	10	15	21	28	41	57	76	97	100															
	Less than 3 : 1	0	7	8	9	11	14	21	32	45	62	81	100														
60	3 : 1 to 10 : 1	0	7	8	10	13	16	25	36	49	66	85	100														
	over 10 : 1	0	8	10	14	20	25	38	51	67	85	100															
	Less than 3 : 1	0	7	7	8	10	12	18	26	36	48	62	79	98	100												
80	3 : 1 to 10 : 1	0	7	8	9	11	14	21	29	40	52	67	84	100													
	over 10 : 1	0	8	9	13	17	22	32	44	56	70	86	100														
	Less than 3 : 1	0	7	7	8	9	11	16	22	30	40	51	65	80	97	100											
100	3 : 1 to 10 : 1	0	7	8	9	11	13	18	25	34	44	56	69	84	100												
	over 10 : 1	0	7	9	12	16	20	29	39	49	61	74	89	100													

Table 29. National Building Code of Canada 2015 Table 3.2.3.1.D.

Table 3.2.3.1.D.
Unprotected Opening Limits for a Building or Fire Compartment that is Sprinklered Throughout
Forming Part of Article 3.2.3.1.

Exposing Building Face	Area of *Unprotected Opening* for Groups A, B, C, D and F, Division 3 *Occupancies*, %											
Max. Area, m²	*Limiting Distance*, m											
	0	1.2	1.5	2.0	2.5	3	4	5	6	7	8	9
10	0	16	24	42	66	100						
15	0	16	20	34	50	74	100					
20	0	16	20	30	42	60	100					
25	0	16	18	26	38	52	90	100				
30	0	14	18	24	34	46	78	100				
40	0	14	16	22	30	40	64	96	100			
50	0	14	16	20	28	36	56	82	100			
60	0	14	16	20	26	32	50	72	98	100		
80	0	14	16	18	22	28	42	58	80	100		
100	0	14	16	18	22	26	36	50	68	88	100	
150 or more	0	14	14	16	20	22	30	40	52	66	82	100

Table 30. National Building Code of Canada 2015 Table 3.2.3.7.

Table 3.2.3.7.
Minimum Construction Requirements for Exposing Building Faces
Forming Part of Sentences 3.2.3.7.(1) and (2)

Occupancy Classification of *Building* or *Fire Compartment*	Maximum Area of *Unprotected Openings* Permitted, % of *Exposing Building Face* Area	Minimum Required *Fire-Resistance Rating*	Type of Construction Required	Type of Cladding Required
Group A, B, C, D, or Group F, Division 3	0 to 10	1 h	*Noncombustible*	*Noncombustible*
	> 10 to 25	1 h	*Combustible* or *Noncombustible*	*Noncombustible*
	> 25 to 50	45 min	*Combustible* or *Noncombustible*	*Noncombustible*
	> 50 to < 100	45 min	*Combustible* or *Noncombustible*	*Combustible* or *Noncombustible*(1)
Group E, or Group F, Division 1 or 2	0 to 10	2 h	*Noncombustible*	*Noncombustible*
	> 10 to 25	2 h	*Combustible* or *Noncombustible*	*Noncombustible*
	> 25 to 50	1 h	*Combustible* or *Noncombustible*	*Noncombustible*
	> 50 to < 100	1 h	*Combustible* or *Noncombustible*	*Combustible* or *Noncombustible*

Notes to Table 3.2.3.7.:
(1) The cladding on Group C *buildings* conforming to Article 3.2.2.50. and on Group D *buildings* conforming to Article 3.2.2.58. shall be *noncombustible*.

Table 31. NBCC occupancy classifications.

Group letter	Occupancy type
A	Assembly
B	Care, treatment, or detention
C	Residential
D	Business and personal services
E	Mercantile
F	Industrial (Divisions 1 to 3 = high, medium, and low risk)

Exceptions for combustible cladding on non-combustible constructed buildings are included in clause 3.1.5.5.

> 3.1.5.5 Combustible Cladding on Exterior Walls
>
> (1) Except as provided in Sentences (2) and (3), combustible cladding is permitted to be used on an exterior wall assembly in a building required to be of non-combustible construction, provided
>
> (a) The building is
>
> (i) Not more than 3 storeys in building height
>
> (ii) Sprinklered throughout, and
>
> (b) When tested in accordance with CAN/ULC-S134, "Fire Test of Exterior Wall Assemblies," the wall assembly satisfies the following criteria for testing and conditions of acceptance (see Note A-3.1.5.5.(1)(b)(i)):
>
> (i) Flaming on or in the wall assembly does not spread more than 5 m above the opening (see Note A-3.1.5.5.(1)(b)(i)), and
>
> (ii) The heat flux during the flame exposure on the wall assembly is not more than 35 kW/m² measured at 3.5 m above the opening (see Note A-3.1.5.5.(1)(b)(ii)).
>
> (2) Except as permitted by Articles 3.2.3.10. and 3.2.3.11., where the limiting distance in Tables 3.2.3.1.-B to 3.2.3.1.-E permits an area of unprotected openings of not more than 10% of the exposing building face, the construction requirements of Table 3.2.3.7. shall be met.

Exposing building face is defined as:

> that part of the exterior wall of a building that faces one direction and is located between ground level and the ceiling of its top storey or, where a building is divided into fire compartments, the exterior wall of a fire compartment that faces one direction.

Limiting distance is defined as:

> the distance from an exposing building face to a property line, the centre line of a street, lane or public thoroughfare, or to an imaginary line between 2 buildings or fire compartments on the same property, measured at right angles to the exposing building face.
>
> **A-3.2.3. Fire Protection Related to Limiting Distance versus Separation Between Buildings.**
>
> Code provisions that address protection against fire spread from building to building use the limiting distance (see the definition in Article 1.4.1.2. of Division A) for a building rather than using the distance between adjacent buildings on separate properties, since this would result in situations where the design and construction of a building on one property affects the design and construction of a building on an adjacent property.

The Code requirements that deal with reducing the probability of building-to-building fire spread were originally developed based on the assumption that the exposing building faces of adjacent buildings are of similar size and configuration, and are equidistant from the shared property line. Where buildings are of different sizes, the smaller building may be subject to a higher heat flux in the event of a fire compared to the larger building. Where buildings are closely spaced and not equidistant from the property line, the construction of the building with the greater limiting distance does not recognize the proximity of the building with the lesser limiting distance.

The Code has more stringent requirements for buildings with lesser limiting distance as regards the maximum area and spacing of unprotected openings, and the construction, cladding and fire resistance of walls. This increased stringency recognizes that the fire hazard is greater where buildings are closer together and that adjacent buildings may have exposing building faces of different sizes, configurations or limiting distances, which could further increase the hazard.

The authority having jurisdiction may also address limiting distances through legal agreements with the parties involved that stipulate that the limiting distance be measured to a line that is not the property line. Such agreements would normally be registered with the titles of both properties."

The NBCC includes requirements for roof assemblies. These are covered in sections 3.1.14 and 3.1.15.

3.1.14 Roof Assemblies

3.1.14.1 Fire Retardant-Treated Wood Roof Systems

(1) If a fire-retardant-treated wood roof system is used to comply with the requirements of Subsection 3.2.2, the roof deck assembly shall meet the conditions of acceptance of CAN/ULC-S126, "Test for Fire Spread Under Roof-Deck Assemblies."

(2) Supports for the roof deck assembly referred to in Sentence (1) shall consist of

(a) fire-retardant-treated wood,

(b) heavy timber construction,

(c) non-combustible construction, or

(d) a combination thereof.

3.1.14.2 Metal Roof Deck Assemblies

(1) Except as permitted by Sentence (2) a metal roof deck assembly shall meet the conditions of acceptance of CAN/ULC-S126, "Test for Fire Spread Under Roof-Deck Assemblies, if

(a) it supports a combustible material above the deck that could propagate to a fire beneath the roof deck assembly, and

(b) the deck is used to comply with the requirements of Sentences 3.2.2.25.(2), 3.2.2.32.(2), 3.2.2.60.(2), 3.2.2.66.(2), and 3.2.2.83.(2) for non-combustible construction.

(2) The requirements of Sentence (1) are waived provided

(a) the combustible material above the roof deck is protected by not less than 12.7 mm thick gypsum board, mechanically fastened to a supporting assembly if located beneath the roof deck, or by a thermal barrier conforming to one of Clauses 3.1.5.12.(2)(c) to (e) that is located

(i) on the underside of the combustible material, or

(ii) beneath the roof deck.

(b) the building is sprinklered throughout, or

(c) the roof assembly has a fire-resistance rating not less than 45 min.

3.1.15 Roof Covering

3.1.15.1 Roof Covering Classification

(1) A roof covering classification shall be determined in conformance with CAN/ULC-S107, "Fire Tests of Roof Coverings."

3.1.15.2 Roof Coverings

(1) Except as provided in Sentences (2) and (3), every roof covering shall have a Class A, B or C classification as determined in accordance with Article 3.1.15.1.

(2) A roof covering is not required to have a Class A, B or C classification for

(a) a tent,

(b) an air-supported structure, or

(c) a building of Group A, Division 2 occupancy not more than 2 storeys in building height and not more than 1000 m² in building area provided the roof covering is underlaid with noncombustible material.

(3) Except as permitted by Sentence (4), roof coverings on buildings conforming to Article 3.2.2.50. or 3.2.2.58. shall have a Class A classification where the roof height is greater than 25 m measured from the floor of the first storey to the highest point of the roof.

(4) Where buildings conforming to Article 3.2.2.50. or 3.2.2.58. include non-contiguous roof assemblies at different elevations, the roof assemblies referred to in Sentence (3) are permitted to be evaluated separately to determine the roof covering classification required."

The Canadian CAN/ULC S-107 roof covering standard is considered functionally identical to the UL 790 (UL, 2004), NFPA 256 (NFPA, 2003) and ASTM E108 (ASTM, 2016) standards (Messerschmidt & Scott, 2013).

A.4 United Kingdom

External walls require a level of fire resistance required by Approval Document B Volume 2 Table A2 (Table 32). If the external wall is within 1 m from any point of the relevant boundary, the fire resistance must be based on exposure from both sides. If the external wall is more than 1 m from the boundary, exposure is from inside the building only.

Table 32. UK ADB Volume 2 Table A2.

Table A2 Minimum periods of fire resistance

Purpose group of building	Minimum periods of fire resistance (minutes) in a:					
	Basement storey [5] including floor over		Ground or upper storey			
	Depth (m) of a lowest basement		Height (m) of top floor above ground, in a building or separated part of a building			
	More than 10	Not more than 10	Not more than 5	Not more than 18	Not more than 30	More than 30
1. Residential:						
a. Block of flats						
– not sprinklered	90	60	30*	60**†	90**	Not permitted
– sprinklered	90	60	30*	60**†	90**	120**
b. Institutional	90	60	30*	60	90	120#
c. Other residential	90	60	30*	60	90	120#
2. Office:						
– not sprinklered	90	60	30*	60	90	Not permitted
– sprinklered [2]	60	60	30*	30*	60	120#
3. Shop and commercial:						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered [2]	60	60	30*	60	60	120#
4. Assembly and recreation:						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered [2]	60	60	30*	60	60	120#
5. Industrial:						
– not sprinklered	120	90	60	90	120	Not permitted
– sprinklered [2]	90	60	30*	60	90	120#
6. Storage and other non-residential:						
a. any building or part not described elsewhere:						
– not sprinklered	120	90	60	90	120	Not permitted
– sprinklered [2]	90	60	30*	60	90	120#
b. car park for light vehicles:						
i. open sided car park [3]	Not applicable	Not applicable	15*+	15*+ [4]	15*+ [4]	60
ii. any other car park	90	60	30*	60	90	120#

Small unprotected areas are allowed in an external wall situated within 1 m of the relevant boundary as specified in section 13.10 with constraints shown in Diagram 44 (Figure 48). For external walls greater than 1 m from any point on the relevant boundary, allowable unprotected areas can be calculated using the methods in BRE 187 (Chitty, 2014), which is discussed in section 2.3.2. Areas as shown in Diagram 44 can be disregarded in these calculations.

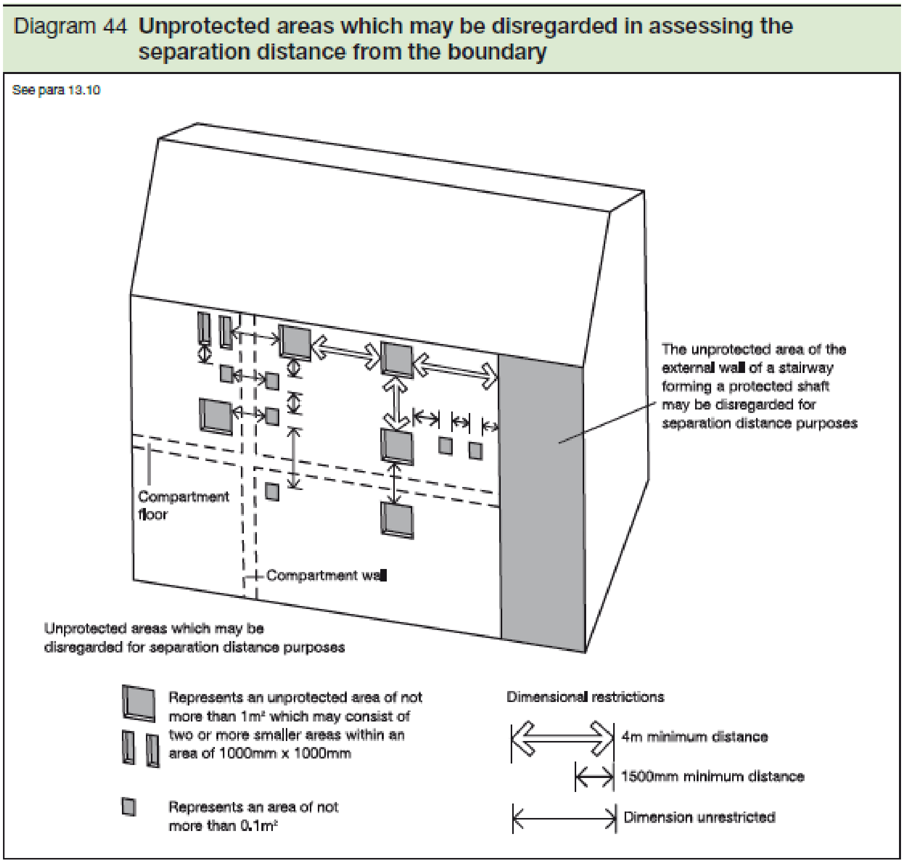


Figure 48. UK ADB Volume 2 Diagram 44.

Roof coverings in general have an external fire resistance requirement in the UK to prevent penetration of fire into the building and to prevent fire spread across the roof. Performance is determined by reference to either BS 476-3:2004 or BS EN 13501-5:2005 *Fire classification of construction products and building elements – Classification using data from external fire exposure to roof tests*.

The UK external fire resistance requirements take distance to the boundary into account. Rooflights are limited to a minimum distance of 6 m from the boundary. The roof class ratings are also dependent on the distance to the boundary. Only national class AA, AB, or AC (European class B_{ROOF}(t4)) roof coverings are allowed within 6 m of any point of a relevant boundary.

A.5 United States

A.5.1 IBC

The 2015 IBC categorises five types of construction as shown in Table 33. There are different criteria for external wall fire resistance based on separation as shown in Table 34. In general, all types of construction require some level of fire resistance up to a separation of 10 ft (3 m). From 10 ft to 30 ft (3 m to 9 m), unprotected non-combustible and unprotected wood frame construction buildings do not require fire resistance except for occupancy group H (high hazard), while all other types of construction require at least 1 hour of fire resistance rating. Beyond 30 ft (9 m), no types of construction require external wall fire resistance (unless otherwise required for load bearing elements).

Table 33. IBC 2015 Types of construction and common usage.

Type	Description	Common Usage
I-A	Fire Resistive Non-Combustible	High rise/Group I occupancies (institutional)
I-B	Fire Resistive Non-Combustible	Mid rise office/Group R buildings (residential)
II-A	Protected Non-Combustible	Newer school buildings
II-B	Unprotected Non-Combustible	Commercial buildings
III-A	Protected Combustible	Typically brick or block walls with wooden roof or floor assembly
III-B	Unprotected Combustible	Older warehouse districts
IV	Heavy Timber	"Mill" construction
V-A	Protected Wood Frame	Newer apartment buildings
V-B	Unprotected Wood Frame	Single family homes/garages

Table 34. IBC 2015 Table 602.

TABLE 602 FIRE-RESISTANCE RATING REQUIREMENTS FOR EXTERIOR WALLS BASED ON FIRE SEPARATION DISTANCE[a, d, g]

FIRE SEPARATION DISTANCE = X (feet)	TYPE OF CONSTRUCTION	OCCUPANCY GROUP H[e]	OCCUPANCY GROUP F-1, M, S-1[f]	OCCUPANCY GROUP A, B, E, F-2, I, R, S-2, U[h]
X < 5[b]	All	3	2	1
5 ≤ X < 10	IA	3	2	1
	Others	2	1	1
10 ≤ X < 30	IA, IB	2	1	1[c]
	IIB, VB	1	0	0
	Others	1	1	1[c]
X ≥ 30	All	0	0	0

Section 705.8 of the 2015 IBC has requirements for allowable areas of openings in external walls as shown in Table 35.

Table 35. IBC 2015 Table 705.8.

TABLE 705.8 MAXIMUM AREA OF EXTERIOR WALL OPENINGS BASED ON FIRE SEPARATION DISTANCE AND DEGREE OF OPENING PROTECTION

FIRE SEPARATION DISTANCE (feet)	DEGREE OF OPENING PROTECTION	ALLOWABLE AREA[a]
0 to less than 3[b, c, k]	Unprotected, Nonsprinklered (UP, NS)	Not Permitted[k]
	Unprotected, Sprinklered (UP, S)[i]	Not Permitted[k]
	Protected (P)	Not Permitted[k]
3 to less than 5[d, e]	Unprotected, Nonsprinklered (UP, NS)	Not Permitted
	Unprotected, Sprinklered (UP, S)[i]	15%
	Protected (P)	15%
5 to less than 10[e, f, j]	Unprotected, Nonsprinklered (UP, NS)	10%[h]
	Unprotected, Sprinklered (UP, S)[i]	25%
	Protected (P)	25%
10 to less than 15[e, f, g, j]	Unprotected, Nonsprinklered (UP, NS)	15%[h]
	Unprotected, Sprinklered (UP, S)[i]	45%
	Protected (P)	45%
15 to less than 20[f, g, j]	Unprotected, Nonsprinklered (UP, NS)	25%
	Unprotected, Sprinklered (UP, S)[i]	75%
	Protected (P)	75%
20 to less than 25[f, g, j]	Unprotected, Nonsprinklered (UP, NS)	45%
	Unprotected, Sprinklered (UP, S)[i]	No Limit
	Protected (P)	No Limit
25 to less than 30[f, g, j]	Unprotected, Nonsprinklered (UP, NS)	70%
	Unprotected, Sprinklered (UP, S)[i]	No Limit
	Protected (P)	No Limit
30 or greater	Unprotected, Nonsprinklered (UP, NS)	No Limit
	Unprotected, Sprinklered (UP, S)[i]	No Limit
	Protected (P)	No Limit

For SI: 1 foot = 304.8 mm.
UP, NS = Unprotected openings in buildings not equipped throughout with an automatic sprinkler system in accordance with Section 903.3.1.1.
UP, S = Unprotected openings in buildings equipped throughout with an automatic sprinkler system in accordance with Section 903.3.1.1.
P = Openings protected with an opening protective assembly in accordance with Section 705.8.2.
a. Values indicated are the percentage of the area of the exterior wall, per story.
b. For the requirements for fire walls of buildings with differing heights, see Section 706.6.1.
c. For openings in a fire wall for buildings on the same lot, see Section 706.8.
d. The maximum percentage of unprotected and protected openings shall be 25 percent for Group R-3 occupancies.
e. Unprotected openings shall not be permitted for openings with a fire separation distance of less than 15 feet for Group H-2 and H-3 occupancies.
f. The area of unprotected and protected openings shall not be limited for Group R-3 occupancies, with a fire separation distance of 5 feet or greater.
g. The area of openings in an open parking structure with a fire separation distance of 10 feet or greater shall not be limited.
h. Includes buildings accessory to Group R-3.
i. Not applicable to Group H-1, H-2 and H-3 occupancies.
j. The area of openings in a building containing only a Group U occupancy private garage or carport with a fire separation distance of 5 feet (1523 mm) or greater shall not be limited.
k. For openings between S-2 parking garage and Group R-2 building, see Section 705.3, Exception 2.

Exceptions are permitted for the first storey above grade plane in sentence 705.8.1 for other than H occupancies (high hazard).

The 2015 IBC requires roof coverings to meet minimum classifications based on testing to ASTM E108 (ASTM, 2016) or UL 790 (UL, 2004). These test standards measure the reaction of a roof to external fire exposures similar to the UK roof requirements discussed in section 7.2A.4 (Messerschmidt & Scott, 2013) and provide three levels of classification: A (severe fire exposure), B (moderate fire exposure) and C (minimal fire exposure) (UL, 2014).

IBC 2015 requirements for different types of construction are given in Table 36.

The 2015 IBC also has requirements for above-deck roof thermal insulation to pass the NFPA 276 or UL 1256 test when tested as an assembly (section 1508.1). These tests look at the contribution of roof assemblies to fire heat release rate per unit area from an internal fire exposure (Messerschmidt & Scott, 2013). The test criteria for NFPA 276 is that the roof assembly should not contribute more than 410 Btu/ft²/min (78 kW/m²) at 3 minutes, 390 Btu/ft²/min (74 kW/m²) at 5 minutes, 360 Btu/ft²/min (68 kW/m²) at 10 minutes and an average 285 Btu/ft²/min (54 kW/m²) over the 30-minute duration of the test.

Table 36. IBC 2015 Table 1505.1

TABLE 1505.1[a, b] MINIMUM ROOF COVERING CLASSIFICATION FOR TYPES OF CONSTRUCTION

IA	IB	IIA	IIB	IIIA	IIIB	IV	VA	VB
B	B	B	C[c]	B	C[c]	B	B	C[c]

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m².

a. Unless otherwise required in accordance with the *International Wildland-Urban Interface Code* or due to the location of the building within a fire district in accordance with Appendix D.

b. Nonclassified roof coverings shall be permitted on buildings of Group R-3 and Group U occupancies, where there is a minimum fire-separation distance of 6 feet measured from the leading edge of the roof.

c. Buildings that are not more than two stories above grade plane and having not more than 6,000 square feet of projected roof area and where there is a minimum 10-foot fire-separation distance from the leading edge of the roof to a lot line on all sides of the building, except for street fronts or public ways, shall be permitted to have roofs of No. 1 cedar or redwood shakes and No. 1 shingles constructed in accordance with Section 1505.7.

A.5.2 NFPA

In Appendix A of NFPA 101, clause A.3.3.49.1 Fire Compartment states:

> In the provisions for fire compartments utilizing the outside walls of a building, it is not intended that the outside wall be specifically fire resistance rated, unless required by other standards. Likewise, it is not intended that outside windows or doors be protected, unless specifically required for exposure protection by another section of this Code or by other standards.

General fire resistance requirements for different types of construction from NFPA 5000 are shown in Table 37. Construction types are similar to those in Table 33 for the IBC. The three-digit codes given as sub-types are nominal fire resistance ratings in hours for exterior-bearing walls (first digit), column, beams and trusses (second digit) and floors (third digit). In general, exterior loadbearing walls do not require fire resistance, and exterior bearing walls and roofs require fire resistance for all types of construction, except for cases of type II, III, and V construction where no fire resistance is required.

Table 37. NFPA 5000 Table 7.2.1.1.

Table 7.2.1.1 Fire Resistance Ratings for Type I Through Type V Construction (hr)

	Type I		Type II			Type III		Type IV	Type V	
Construction Element	**442**	**332**	**222**	**111**	**000**	**211**	**200**	**2HH**	**111**	**000**
Exterior Bearing Walls[a]										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0[b]	2	2	2	1	0[b]
Supporting one floor only	4	3	2	1	0[b]	2	2	2	1	0[b]
Supporting a roof only	4	3	1	1	0[b]	2	2	2	1	0[b]
Interior Bearing Walls										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	2	1	0
Supporting one floor only	3	2	2	1	0	1	0	1	1	0
Supporting roofs only	3	2	1	1	0	1	0	1	1	0
Columns										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	3	2	2	1	0	1	0	H	1	0
Supporting roofs only	3	2	1	1	0	1	0	H	1	0
Beams, Girders, Trusses, and Arches										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	2	2	2	1	0	1	0	H	1	0
Supporting roofs only	2	2	1	1	0	1	0	H	1	0
Floor/Ceiling Assemblies	2	2	2	1	0	1	0	H	1	0
Roof/Ceiling Assemblies	2	1½	1	1	0	1	0	H	1	0
Interior Nonbearing Walls	0	0	0	0	0	0	0	0	0	0
Exterior Nonbearing Walls[c]	0[b]	0[b]	0[b]	0[b]	0[b]	0[b]	0[b]	0[b]	0[b]	0[b]

H: Heavy timber members (*see text for requirements*).
[a]See 7.3.2.1.
[b]See Section 7.3.
[c]See 7.2.3.2.12, 7.2.4.2.3, and 7.2.5.6.8.

Additional NFPA 5000 requirements for external wall fire resistance based on horizontal fire spread are given in Table 38. Most buildings require fire resistance with horizontal separations of up to 3 m, with high-hazard industrial occupancy buildings requiring fire resistance with horizontal separations of up to 9 m.

Table 38. NFPA 5000 Table 7.3.2.1.

Δ Table 7.3.2.1 Fire Resistance Ratings for Exterior Walls (hr)

	Horizontal Separation ft (m)				
Occupancy Classification	**0 to 5 (0 to 1.5)**	**>5 to ≤10 (>1.5 to ≤3)**	**>10 to ≤30 (>3 to ≤9)**	**>30 (>9)**	**Opening Protectives**
Assembly, educational, day care, health care, ambulatory health care, detention and correctional, residential, residential board and care, business, industrial, and storage occupancies with low hazard contents	1	1	0	0	See Table 7.3.5(a).
Mercantile and industrial and storage occupancies with ordinary hazard contents	2	1	0	0	See Table 7.3.5(b).
Industrial and storage occupancies with high hazard contents exceeding the MAQ per control area as set forth in 34.1.3 and complying with Protection Level 1, Protection Level 2, or Protection Level 3	See Chapter 34 for minimum requirements.				
Industrial and storage occupancies with high hazard contents exceeding the MAQ per control area as set forth in 34.1.3 and complying with Protection Level 4 or Protection Level 5	3	2	1	0	See Table 7.3.5(b).

NFPA 5000 allowable percentages of unprotected openings in exterior walls for low-hazard buildings are given in Table 39. These areas can be doubled under clause 7.3.5.5 if either the "building is protected throughout with an approved, electrically supervised automatic sprinkler system in accordance with NFPA 13, 13D, or 13R" or if "the openings are protected with a fire window assembly or other listed opening protectives having a fire protection rating in accordance with Table 7.3.5.5" (Table 40).

Table 39. NFPA 5000 Table 7.3.5(a).

Δ Table 7.3.5(a) Maximum Allowable Area of Unprotected Openings (percentage of exterior walls) — for Assembly, Educational, Day-Care, Health Care, Ambulatory Health Care, Detention and Correctional, Residential, Residential Board and Care, Business, Industrial, and Storage Occupancies with Low Hazard Contents as Required by Table 7.3.2.1

Horizontal Separation (ft)	Maximum Area of Exposing Building Face (ft^2)																		
	100	150	200	250	300	400	500	600	700	800	900	1000	1500	2000	2500	3500	5000	10,000	≥20,000
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	9	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7
5	12	11	10	9	9	9	8	8	8	8	8	8	7	7	7	7	7	7	7
6	18	15	13	12	11	10	10	9	9	9	9	8	8	8	8	7	7	7	7
7	25	20	17	15	14	12	11	11	10	10	10	9	9	8	8	8	8	7	7
8	33	25	21	19	17	15	14	13	12	11	11	11	10	9	9	8	8	7	7
9	43	32	27	23	21	18	16	15	14	13	12	12	11	10	9	9	8	8	7
10	55	40	33	28	25	21	19	17	16	15	14	13	12	11	10	9	9	8	7
>10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

For SI units, 1 ft = 0.3048 m; 1 ft^2 = 0.093 m^2.

Table 40. NFPA 5000 Table 7.3.5.5.

Δ Table 7.3.5.5 Minimum Fire Protection Ratings for Exterior Opening Protectives

Wall Fire Resistance Rating (hr)	Fire Protection Rating (hr)
2	1½
1	¾

NFPA 5000 has similar exterior roof fire exposure requirements to the IBC as shown in Table 41.

Table 41. NFPA 5000 Table 38.2.2.

Table 38.2.2 Minimum Roof-Covering Classification

Type of Construction	Minimum Roof Covering Classification
Type I (442)	B
Type I (332)	B
Type II (222)	B
Type II (111)	B
Type II (000)	C
Type III (211)	B
Type III (200)	C
Type IV (2HH)	B
Type V (111)	B
Type V (000)	C

A.6 Sweden

General reaction-to-fire requirements for external walls are covered in section 5:51 of the Swedish building regulations (Boverket, 2016) and are not covered here.

Requirements for windows in exterior walls are as follows:

> 5:553 Windows in exterior walls
>
> Windows belonging to separate fire compartments in the same building and facing each other or positioned above each other vertically, shall be designed and located to ensure fire spread between fire compartment boundaries is restricted. It shall not be possible for windows subject to fire resistance classification to be opened other than by a tool, key, or similar (BFS 2011:26).
>
> General recommendation
>
> The requirements in the provision or equivalent apply to windows, glazed surfaces, or similar that are situated so that direct thermal radiation from a fire can occur from one window to the other. Examples of designs that comply with the requirements of the above provision regarding prevention of the spread of fire are contained in Table 5.553 (Table 41). Thermal radiation is assumed to occur at right angles to, and up to an angle of 135° from, the plane of the window surface. If the angle of an internal corner is less than 60°, the requirements for opposite, parallel exterior walls apply (BFS 2011:26)."

Table 42. Swedish building regulations Table 5:553.

Table 5:553 ***Examples of the design of windows in exterior walls facing one another or placed one above the other vertically. This applies between fire compartments with requirements equivalent to EI 60 or less.***

Relative positions	Distance (meters) between windows	Design of exterior walls
Windows in opposite (parallel) exterior walls	< 5.0 ≥ 5.0	One window in class E 30, or both in E 15 –
Windows in inner corners	< 2.0 ≥ 2.0	One window in class E 30, or both in E 15 –
Windows placed above each other vertically	< 1.2 ≥ 1.2	One window in class E 30, or both in E 15 –

(BFS 2013:14).

> 5:6 Protection against the spread of fire between buildings
>
> 5:61 General
>
> Buildings shall be designed with adequate protection against fire spread between buildings (BFS 2011:26).
>
> General recommendation
>
> Adequate protection is achieved if buildings are constructed at a distance of more than 8 meters. Adequate protection is achieved if the fire spread between

buildings is limited to protection that corresponds to the maximum requirement for fire compartments or firewalls in each building. Combined buildings with more than two storeys should be separated with a firewall. If there is a glazed balcony, the distance should be calculated from the balcony slab's outer edge. Other protruding parts, such as roof projection and balcony, which protrude out more than 0.5 meters, should be included in the calculation of the distance between buildings."

5:62 Roof covering

Roof coverings on buildings shall be designed to ensure ignition is made difficult, fire spread is restricted and that they only give a limited contribution to a fire (BFS 2011:26).

General recommendation

Making ignition difficult means, for example, protection against glowing airborne particles or sparks.

Roof coverings should be designed with materials of class A2-s1,d0 or with materials of at least class B_{ROOF} (t2) on underlying material of class A2-s1,d0.

Combustible roof coverings, in at least class B_{ROOF} (t2), can be used on combustible surfaces of buildings which are located at least 8 meters apart, or in single-family houses.

Combustible roof coverings on combustible surfaces should not be installed on buildings, except single-family houses, within 8 meters from a chimney connected to a boiler with combustion from solid fuels.

Guidelines on protection against fire spread from adjacent roofs are contained in section 5:536 which also apply between buildings. (BFS 2014:3).

Appendix B: Wood crib specifications