Study Report

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Preparing the foundation for risk-informed fire safety design

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Preface

This report is the first step in determining the supporting data requirements and availability for a risk-informed fire safety design approach, using the New Zealand Building Code and C/VM2.

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Abstract

This study report provides a summary of a research project that aimed to identify uncertainties in the current parameters used to validate fire safety designs using the Verification Method C/VM2.

The New Zealand Building Code and Verification Method C/VM2 were analysed to identify the engineering parameters that are used in various calculations for fire safety modelling.

It is proposed that the uncertainties in these parameters can be characterised using statistical probability density functions (where data is available) giving a range of potential outcomes in order to form the basis of a risk-informed fire safety design.

A wide range of parameters were identified, and a literature review undertaken to determine whether the parameters have been investigated previously and have statistical distributions available or not. The literature review covered parameters that fell into three main areas: those required for calculating the available safe egress time (ASET), the tenability limits for occupants and the required safe egress time (RSET). The main parameters included fire growth rate, heat release rate, fire load energy density, species production, ventilation conditions and movement times.

Further work will be required to identify statistical distributions for parameters not yet classified at this time. That said, probably of greater importance would be a sensitivity analysis to determine which of these identified parameters have the greatest influence on the outcome of engineering analyses. In this way, research can be focused on the key parameters required and the greatest research impact can be targeted.

Keywords

NZBC, C/VM2, risk, statistical distributions, HRR, growth rate, FLED, species yield, ASET, RSET, ventilation, glazing, smoke, evacuation.

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Executive summary

This report is the first step in determining the supporting data requirements and availability for a risk-informed fire safety design approach using the New Zealand Building Code and Verification Method C/VM2.

A literature review was undertaken to identify parameters in the NZBC and C/VM2. There is substantial uncertainty in some of the parameters required for fire safety modelling.

The commentary for C/VM2 states:

> This document does not provide a comprehensive, technical justification of the values selected for use in Clauses C1 to C6 and Verification Method C/VM2 … the fire research community simply has not provided methodologies for addressing the design issues faced in common engineering practice. In fact, there are a number of historic values within all of the international codes that are commonly accepted but have no technical basis. (MBIE, 2013)

These uncertainties can be characterised using statistical distributions based on available data to form the basis of a risk-informed fire safety design.

A wide range of parameters were identified, some of which had been investigated previously and have statistical distributions available and others that do not. The parameters investigated fell into three main areas: those required for calculating the available safe egress time (ASET), the tenability limits for occupants and the required safe egress time (RSET). The main parameters included fire growth rate, heat release rate, fire load energy density, species production, ventilation conditions and movement times.

Further work will be required to identify statistical distributions for parameters not yet classified at this time. That said, probably of greater importance would be a sensitivity analysis to determine which of these identified parameters have the greatest influence on the outcome of engineering analyses. In this way, research can be focused on the key parameters required and the greatest research impact can be targeted.

1. Introduction

The New Zealand Building Code (NZBC) is performance based, meaning that, if a design solution can be demonstrated to meet the relevant performance criteria, it must be accepted by building consent authorities.

Fire safety is covered by NZBC clauses C1 to C6 *Protection from fire* (DBH, 2012a). Along with clause A3 *Building importance levels* (DBH, 2012b), these define the performance criteria a building is required to meet. In 2012, the Department of Building and Housing (now the Ministry of Building, Innovation and Employment, MBIE) released *C/VM2 Verification Method: Framework for Fire Safety Design* (MBIE, 2017) and an accompanying commentary for Verification Method C/VM2 (MBIE, 2013).

Compliance with the NZBC can be demonstrated in several ways:

- If the building is within scope, the use of Acceptable Solutions (C/AS1 and C/AS2), which are deemed to comply (MBIE, 2019).
- Use of Verification Method C/VM2 (the VM).
- If the building is not within the scope of C/AS1, C/AS2 or C/VM2, Alternative Solutions requiring specific fire engineering design must be used.

The VM provides a means for demonstrating compliance with NZBC clauses C1 to C6 and requires that the designer demonstrates how the proposed design will meet the performance criteria using 10 design scenarios. Each scenario represents a different aspect of fire performance of the building and might be demonstrated by inspection or require a more detailed analysis. Table 1.1 in the VM, reproduced as Table 1 below, shows a summary of the design scenarios, the NZBC objective to be met, the criteria for compliance and the 'expected method' of demonstrating compliance.

The scope of use of the VM is limited to buildings that have simultaneous evacuation strategies that evacuate immediately to the outside of the building and with typical fire hazards. The VM gives examples of buildings that are outside the scope of the VM including hospitals, care homes, stadia, principal transport terminals, large shopping malls (greater than 10,000 m_2 and containing mezzanine floors), tall buildings (greater than 60 m or 20 storeys in height) and tunnels.

The commentary states:

> This document does not provide a comprehensive, technical justification of the values selected for use in Clauses C1 to C6 and Verification Method C/VM2 … the fire research community simply has not provided methodologies for addressing the design issues faced in common engineering practice. In fact, there are a number of historic values within all of the international codes that are commonly accepted but have no technical basis. (MBIE, 2013)

Fire is inherently difficult to predict with any certainty due to the significant uncertainty with the large number of the variables involved. The VM could be considered to test the worst-case fire event and not the most likely. With this in mind, the values defined in the NZBC and the VM are assumed to be conservative (although this has yet to be proven) and might lead to an overly conservative design where the cost of protection measures might be disproportionate to the level of risk.

In order to transition to a more risk-informed design process, we need evidence to support probabilistic data distributions rather than deterministic values, as currently defined.

The purpose of the research summarised in this report is to assess the current rules and parameters in the NZBC and the VM (and the bodies of evidence behind them) where possible to provide a technical justification and also to identify statistical probability density functions (PDFs) that could be applied to inputs to provide a more risk-informed design output.

Table 1. C/VM2 design scenarios (Table 1.1 extracted from C/VM2).

Table 1.1 **Key features of design scenarios**

Design scenario		*Building Code* objectives	*Building Code* criteria	Expected method
Keeping people safe				
BE	*Fire* blocks exit (4.1)	C1(a)	C4.5	Solved by inspection
UT	*Fire* in a normally unoccupied room threatening occupants of other rooms (4.2)	C1(a)	C4.3, C4.4	*ASET/RSET* analysis or provide *separating elements*/suppression complying with a recognised Standard
CS	*Fire* starts in a *concealed space* (4.3)	C1(a)	C4.3	Provide *separating elements*/suppression or automatic detection complying with a recognised Standard
SF	Smouldering *fire* (4.4)	C1(a)	C4.3	Provide automatic detection and alarm system complying with a recognised Standard
IS	Rapid *fire* spread involving internal surface linings (4.7)	C1(b)	C3.4	Suitable materials used (proven by testing)
CF	Challenging *fire* (4.9)	C1(a)	C4.3, C4.4	*ASET/RSET* analysis
RC	Robustness check (4.10)	C1(a), C1(b), C1(c)	C3.9, C4.5, C5.8, C6.2(d)	Modified *ASET/RSET* analysis
Protecting other property				
HS	Horizontal *fire* spread (4.5)	C1(b), C1(a)	C3.6, C3.7, C4.2	Calculate radiation from *unprotected areas* as specified
Amend 4 Jul 2014 VS	External vertical *fire* spread (4.6)	C1(a), C1(b)	C3.5	Suitable materials used (proven by testing) and *construction* features specified (eg, aprons/spandrels/sprinklers) as required to limit vertical *fire* spread
Firefighting operations				
FO	Firefighting operations (4.8)	C1(b), C1(c)	C3.8, C5.3, C5.4, C5.5, C5.6, C5.7, C5.8, C6.3	Demonstrate firefighter safety

2. NZBC clauses C1 to C6

Clause C1 of the NZBC defines the objectives that clauses C2 to C6 are required to achieve in order to provide protection from fire. The objectives are to:

(a) safeguard people from an unacceptable risk of injury or illness caused by fire
(b) protect other property from damage caused by fire
(c) facilitate firefighting and rescue operations.

However, the NZBC does not define what constitutes an acceptable level of risk by which to judge objective C1(a).

Risk perception also varies. What is acceptable to one person may not be acceptable to another. Equally, the perception of risk may change based upon the number of people being exposed to the risk. For example, it may be considered an 'acceptable' loss to have a single fatality in a house fire but 'unacceptable' to sustain multiple fatalities in shared accommodation (such as a hotel or medium-density housing block).

It is generally accepted that it is the regulator that is responsible for defining an acceptable de facto level of individual and societal risk either in the NZBC or the associated compliance documents.

This report identifies clauses within C2 to C6 that specify parameters or values required for building design or verification and therefore does not contain an analysis of each individual clause.

Numerous clauses within the NZBC require a "low probability" of an occurrence without defining what an acceptable low probability is.

2.1 Clause C3 *Fires affecting areas beyond the fire source*

Clause C3 is aimed at controlling the spread of fire both horizontally and vertically from the source, inside and outside the building.

Clause C3.2 defines the functional requirement that buildings over 10 m high with sleeping uses or other property excluding buildings with importance level (IL) 1 "must be designed and constructed so that there is a low probability of external fire spread to upper floors in the building". The commentary contains no rationale behind the 10 m height limit, and there is a question about where the 10 m is measured to (wall height or roof height). Clause C3.5 goes on to specify the performance requirement that fire must not spread more than 3.5 m vertically from the fire source over the external cladding of the building. Again, there is no technical rationale provided for the choice of 3.5 m spread.

A number of alternative test standards are used to demonstrate compliance with the requirement to limit the spread of fire over the surface cladding of a building. The BS 8414 test apparatus includes thermocouples placed at 2.5 m and 5 m above the fire compartment opening and on the 'wing-wall' (BSI, 2015a, 2015b). BS 8414 does not set out the criteria for a pass/fail. BR135 (BRE, 2013) sets out the general principles for fire performance of cladding systems tested using the BS 8414 standards. Failure due to external fire spread is deemed to have occurred if any of the thermocouples 5 m above the fire compartment opening (or 'wing-wall') exceed 600°C for more than 30 s within 15 minutes of the start time. The design fire in this test is a wood crib

1.5 x 1 x 1 m with a nominal total heat release of 4,500 MJ over 30 minutes with a peak heat release rate (HRR) of 3 ±0.5 MW (BSI, 2015a, 2015b).

AS 5113 (Standards Australia, 2016) uses the same test apparatus as the BS 8414 test and defines failure criteria within the standard mostly in line with BR135 but also includes limitations on the falling debris. The total mass of debris should not exceed 2 kg, and any flaming debris should extinguish in less than 10 s.

The NFPA 285 (NFPA, 2019) test apparatus includes thermocouples 3.05 m above the window opening. Failure due to external fire spread is deemed to occur if the temperature recorded at any of these thermocouple locations exceed 1000°F (538°C) or flames emitting from the surface exceed 3.05 m above the window opening or spread more than 1.52 m from the vertical centreline of the opening. The design fire in this test is provided by a pair of gas burners – a room burner and a window burner. The room burner starts at 687 kW and increases in steps periodically to a maximum of 904 kW over the duration of the test. The window burner is ignited 5 minutes into the test and ranges from 163 kW between 5 and 10 minutes in approximately linear steps each 5 minutes to a maximum of 398 kW between 25 and 30 minutes. The maximum total heat release is 1.3 MW between 25 and 30 minutes. The NFPA 285 test apparatus does not have a 'wing-wall' and therefore cannot be used to demonstrate the performance of corner junction details.

FM 4880 (FM Approvals, 2015) describes a 14' high parallel panel test for aluminium composite panel cladding systems. A 360 kW propane gas burner is ignited at the base of the parallel panels. In order to achieve an unlimited height restriction, a measured peak chemical heat release rate (PCHRR) of ≤830 kW is required. A 50' height restriction is applied to systems achieving a PCHRR of less than or equal to 1100 kW.

None of these test standards can be used to directly demonstrate compliance with the criteria specified in clause C3.5.

Clause C3.4(b) specifies the minimum critical radiant flux (CRF) tested in accordance with ISO 9239-1:2010 for floor coverings in areas of a building, depending on whether sprinklers are fitted or not. The commentary contains no analytical support for the values selected but refers to the Building Code of Australia (ABCB, 2019), which has the same values albeit with slightly different criteria.

Clause C3.6 in conjunction with C3.7 limit the spread of fire to and from adjoining properties. C3.6 specifies the emitted radiant heat flux limit at the boundary (30 kW/m^2) and at 1 m beyond the boundary (16 kW/m^2), while C3.7 restricts the combustibility of materials used in boundary walls located closer than 1 m from the relevant boundary. The exposure time for C3.7 is dependent upon the building importance level. IL1 and IL2 buildings must not ignite within 15 minutes when exposed to a received radiant heat flux of 30 kW/m^2, and IL3 and IL4 building must not ignite within 30 minutes when exposed to a received radiant flux of 30 kW/m^2. The 30 kW/m^2 emitted radiant flux limit specified in C3.6 is consistent with the received limit in C3.7. However, the commentary contains rationale for the lower limit beyond 1 m from the boundary but does not provide any basis for selecting 16 kW/m^2.

Clause C3.8 deals with large unsprinklered buildings within 15 m of a boundary. Where the floor area of the firecell exceeds 5,000 m^2 or a fire load of greater than 20 TJ, at the time of firefighters first applying water, the radiant heat flux at 1.5 m above the ground must be less than 4.5 kW/m^2 and the smoke layer must be more than 2 m above the ground. The time at which this occurs would have to be determined in conjunction with Fire and Emergency New Zealand (FENZ), taking into account detection time, response time and set-up. Claridge and Spearpoint (2013) undertook a study of New Zealand Fire Service (now FENZ) response times to structure fires. They proposed distributions of response speed based on location (urban/rural/metropolitan) and in conjunction with a tool (such as Google Maps) to map the shortest route between the responding appliance and the incident address to provide a likely response time with a 90% confidence level.

It is not clear from the commentary whether this requirement is for safe egress of occupants, which would usually be very low density in this type of building, or to provide tenable conditions for fire service entry into the building. This type of storage building would likely have a lightweight non-fire-rated roof structure that would typically collapse in a structurally significant fire. In this case, it is unlikely FENZ would commit firefighting crews to enter the building unless there were 'persons reported'.

2.2 Clause C4 *Movement to a place of safety*

Clause C4.3 defines the requirements that must be met to maintain a tenable environment within the building and to allow the safe egress of occupants.

Fractional effective dose (FED) is defined in ISO 13943 as the:

> ratio of the exposure dose for an asphyxiant to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility. … As a concept, FED may refer to any effect, including incapacitation, lethality or other end points. (ISO, 2017)

ISO 13571 (ISO, 2012) further defines FED in terms of incapacitation, with an FED of 1.0 being the relative dose of an asphyxiant required to render the average person incapable of effecting their own escape.

Clause C4.3(a) sets the maximum carbon monoxide level an occupant should be exposed to at 0.3 FED, and Clause C4.3(b) sets the maximum total of thermal effects an occupant should be exposed to at 0.3 FED.

The commentary states that, although there is considerable uncertainty due to limited data on the physiological effects of contaminants (and new data points are unlikely given the nature of ethical testing), a 0.3 FED should correspond to approximately 11% of the population being susceptible to the intoxicating effects. This statement appears to come from ISO 13571, which states that, although the distribution of human response to fire gases is not known, a log-normal distribution is considered reasonable, and based on a log-normal distribution, a 0.3 FED would equate to 11.4% of the population being susceptible to less-severe exposure conditions and therefore unable to effect their own escape.

Clause C4.3(c) defines the minimum visibility as a result of smoke obscuration. It states that visibility must not reduce to less than 10 m except in rooms of less than 100 m_2, when visibility may fall to 5 m.

The VM does not account for transient effects in the acceptance criteria. For example, the visibility may drop below the required limit for a short period when a door is opened for egress and then return to an acceptable level once the door is closed again.

The tenability limits are discussed further in section 3.2 when looking at the C/VM2 modelling rules and parameters.

3. C/VM2 modelling rules and parameters

When C/VM2 is used, the primary analytical method for showing compliance with NZBC clauses C1 to C6 includes an analysis of the available safe egress time (ASET) versus the required safe egress time (RSET) as shown in the 'Expected method' column of Table 1.

ASET is a measure of the time until conditions within the compartment become untenable, while RSET is a measure of the time from alerting the occupants to the presence of the fire until they reach a 'place of safety'. ISO 13943 defines a place of safety as a:

> location that is free from danger and from which it is possible to move freely without threat from a fire … In the case of a building fire, it is typically a place outside the building.

3.1 Available safe egress time (ASET)

> Time available for escape for an individual occupant. This is the calculated interval between the time of fire ignition and the time at which conditions become such that the occupant is estimated to be incapacitated (i.e., unable to take effective action to escape to a *place of safety*).' (MBIE, 2013).

ASET is largely dependent upon the parameters specified for the fire (called the design fire), the compartment geometry and ventilation conditions.

The parameters for pre-flashover design fires are defined in the VM in Table 2.1 and Table 2.2 (reproduced below as Table 2 and Table 3 respectively) and include deterministic values for:

- fire growth rate
- peak heat release rate (HRR)
- fire load energy density (FLED)
- species production.

Table 2. C/VM2 design fire characteristics (Table 2.1 extracted from C/VM2).

Table 2.1 Pre-flashover design fire characteristics

	Building use	*Fire* growth rate (kW)	Species	Radiative fraction	Peak *HRR*/ *HRR*/m^2
Amend 4 Jul 2014	All *buildings* including storage with a stack height of less than 3.0 m	$0.0469\ t^2$	Y_{soot} = 0.07 kg/kg Y_{CO} = 0.04 kg/kg ΔH_C = 20 MJ/kg Y_{CO_2} = 1.5 kg/kg[1] Y_{H_2O} = 0.82 kg/kg[1]	0.35	20 MW 500 – 1000 kW/m^2[2] 250 kW/m^2[3]
	Carparks (no stacking)	$0.0117\ t^2$		0.35	
Amend 4 Jul 2014	Capable of storage to a stack height of between 3.0 m and 5.0 m above the floor	$0.188\ t^2$		0.35	50 MW
Amend 4 Jul 2014	Capable of storage to a stack height of more than 5.0 m above the floor and car parks with stacking systems	$0.00068\ t^3\ H$		0.35	1000–2500 kW/m^2[2] 250 kW/m^2[3]

NOTE:
t = time in seconds
H = height to which storage is capable of in metres
Y = *yield* kg/kg
ΔH_C = heat of combustion
(1) As an an alternative to CO_2 + H_2O *yields* use generic fuel as $CH_2O_{0.5}$ and calculate *yields*.
(2) In a CFD model the *fire* is intended to be modelled as a plan area where the size is determined from the peak *HRR*/m^2. A range is provided for *HRR*/m^2 to accommodate different *HRR* and mesh sizes.
(3) Use in a zone model.

Amend 4 Jul 2014

Amend 3 Dec 2013

Table 3. C/VM2 design fire loads (Table 2.2 extracted from C/VM2).

Table 2.2	Design FLEDs for use in modelling fires in C/VM2		
Design *FLED* (MJ/m²)	Activities in the space or room	Examples	
400	1. Display or other large open spaces; or other spaces of low *fire hazard* where the occupants are awake but may be unfamiliar with the *building*.	1. Art galleries, auditoriums, bowling alleys, churches, clubs, community halls, court rooms, day care centres, gymnasiums, indoor swimming pools	
	2. Seating areas without upholstered furniture	2. School classrooms, lecture halls, museums, eating places without cooking facilities	
	3. All spaces where occupants sleep	3. *Household units*, motels, hotels, hospitals, residential care institutions	
	4. Working spaces and where low *fire hazard* materials are stored	4. Wineries, meat processing plants, manufacturing plants	
	5. Support activities of low *fire hazard*	5. Car parks, locker rooms, toilets and amenities, service rooms, plant rooms with plant not using flammable or *combustible* fuels	Amends 3 and 4
800	1. Spaces for business	1. Banks, personal or professional services, police stations (without detention), offices	Amend 3 Dec 2013
	2. Seating areas with upholstered furniture, or spaces of moderate *fire hazard* where the occupants are awake but may be unfamiliar with the *building*	2. Nightclubs, restaurants and eating places, *early childhood centres*, cinemas, *theatres*, libraries	
	3. Spaces for display of goods for sale (retail, non-bulk)	3. Exhibition halls, shops and other retail (non bulk)	
1200	1. Spaces for working or storage with moderate *fire hazard*	1. Manufacturing and processing moderate *fire load* 2. Storage up to 3.0 m high other than *foamed plastics*	
	2. Workshops and support activities of moderate *fire hazard*	3. Maintenance workshops, plant and boiler rooms other than those described elsewhere	Amend 3 Dec 2013
400/tier of car storage	Spaces for multi-level car storage	Car stacking systems. The design floor area over which the design *FLED* applies is the total actual car parking area	
800/m height, with a minimum of 2400	1. Spaces for working or storage with high *fire hazard*	1. Chemical manufacturing and processing, feed mills, flour mills 2. Storage over 3.0 m high of *combustible* materials, including temperature controlled storage	Amend 4 Jul 2014
	2. Spaces for display and sale of goods (bulk retail)	3. Bulk retail (over 3.0 m high)	

3.1.1 Fire growth rate

The fire growth rate is largely determined by the ignition source – the amount and type of fuel and oxygen available.

The fire growth rates defined in the VM are taken from the NFPA t_2 curves. Table 2.1 (reproduced above as Table 2) calls up medium, fast and ultra-fast t_2 curves but also includes a t_3H curve for storage heights in excess of 5 m and car parks with stacking systems. The values in the table are deterministic rather than a distribution of the likely growth rate.

The commentary states that the t_2 curves are taken from NFPA 72, while the t_3H curve was characterised by Ingason (2001) for fires in storage areas where there is a vertical spread, resulting in faster fire growth. For this reason, the growth rate is dependent upon the height of the storage. It should be noted that Ingason only looked at data for rack storage fires between 2.5 and 6.5 m in height and that the value of α was between 0.00068 and 0.00877. The VM uses the slowest growth rate indicated by Ingason (0.00068), which could lead to the possibility that the design is not as conservative in terms of performance.

Nilsson, Johansson and Van Hees (2014) concluded that a fast fire growth rate of 0.047 kW/s^2 with a log-normal distribution would adequately describe 97% of accidental fires but only 91% of arson fires.

A meta-study of upholstered furniture items in both open-burn and compartment conditions using freely available data from a variety of sources was undertaken by Young (2007). She looked at the HRR, time to peak HHR and the total heat released. Growth rate was estimated by visual comparison of the measured HRR to the t^2 growth rate curves rather than measurement of mass loss and was split into categories rather than a numerical solution. This approach demonstrated a trend, with 29% of fires in the medium to fast growth ranges. The data also had limitations around timing. In some cases, there was no account taken of the incipient phase, so although the growth rate may appear to be very slow, in some cases, the incipient phase was long and then a rapid growth occurred as the fire took hold. Holborn, Nolan and Golt (2004) undertook a study of fires investigated and reported in the Real Fire Library (RFL) collected by the Fire Investigation Unit of the London Fire Brigade (LFB) between 1996 and 2000. The frequency histograms for both residential and other properties showed an essentially log-normal distribution for the fire growth rate based on size of fire at discovery and size of fire when the LFB arrived on site and the time between discovery and arrival. Holborn et al. also concluded that, although the distribution did adequately describe the bulk of fire growth rates, it did underestimate when it came to the tails (i.e. very slow growth rates and very fast growth rates).

The Holborn et al. study was based on the stocks of housing and other buildings in the London area. Construction techniques used in the UK are different from New Zealand, where construction is primarily timber-framed in the residential stock. It is unknown how this would affect the data obtained. Fire growth rate in the early stages of fire development would be driven by fuel availability and ventilation, which would be the case for any construction method. Consequently, it is considered that the early fire growth rate would not be significantly different in New Zealand. The difference would come later in the fire development, where the structure would add to the fuel load, unlike bricks and mortar construction.

3.1.2 Heat release rate (HRR)

The peak HHR is defined in Table 2.1 of the VM (reproduced above as Table 2). Depending upon design criteria, the design fire peak HRR of 20 MW or 50 MW is selected. The values in the table are deterministic rather than a distribution of the likely HRR, and it is unclear from the commentary where the values are derived from.

There have been numerous studies looking at the heat release rate of individual objects and items of furniture. These studies looked at individual items burning and therefore did not fully include the effects of radiant feedback in compartments or where multiple items become involved. The 5th edition of the SFPE Handbook (SFPE, 2016) brings together data from these studies and others to provide a wide variety of HRR data for individual items based on research around the globe. Some of this data is becoming obsolete with changes in technology and products. For example, a selection of television sets have been tested over the years, they were small (19–20”) cathode ray tube (CRT) type appliances. Modern TVs are generally liquid crystal displays (LCD), that range up to 75”+ and might have significantly different HRRs as a result of the plastic materials used. The data provided is generally around individual items tested, and the values given are largely deterministic for the specific item tested rather than a statistical distribution of the likely HRR of a particular classification of item.

Young (2007) proposed statistical distributions for armchairs as well as two and three-seat sofas. That said, it was determined that there was insufficient test data to produce a meaningful distribution for beds due to the lack of data points resulting from different incomparable test configurations, i.e. with and without bedding, covers partially turned down and different ignition points. For armchairs, Young proposed a good fit to a normal distribution with a mean of 826 kW and the 98th percentile being 1645 kW. The proposed statistical distribution resulted with the 95th and 98th percentiles being only marginally higher than the test evidence would suggest. Logistic distributions were proposed for both two and three-seat sofas. However, the 95th and 98th percentiles significantly overpredicted when compared against the limited test data. Further data points would be required to be able to refine the statistical distributions for two and three-seat sofas and other items of furniture.

The distributions identified by Young are only representative of ISO 9705-sized compartments (ISO, 2016). There is insufficient data to support distributions for other compartment geometries and/or scaling factors associated with peak HRR, time to peak HRR and total heat released. More evidence would be required to produce distributions of peak HRR from a range of different room types with representative levels of furnishings, although it is not considered practical to cover all compartment geometries.

3.1.3 Fire load energy density (FLED)

The FLED is a combination of:

- the fixed/permanent fire load comprising the combustibles in the building structure, linings, finishings and permanently installed devices, which do not change substantially over the service life of the building
- the variable/movable fire load comprising the combustible furnishings and so on, which may vary throughout the service life of the building.

Where linings are non-combustible and the building structure is protected from fire, the FLED can be considered just the variable/movable fire load per unit of floor area.

In the VM, Table 2.2 defines the FLED based upon the activity being undertaken in the room. The values in the table are deterministic rather than a distribution of the likely FLED, and it is unclear from the commentary where the values are derived from. The commentary states that the values are "loosely" based on a CIB study, but no reference could be found in the VM or commentary.

The VM does not take account of the fixed fire load that may be present in the structure of the building, which is becoming more of a concern with a move to exposed engineered wood products such as cross-laminated timber (CLT) beams, columns and panels. This is of particular concern as not only does the structure contribute to the fire load, but as the structural timbers are consumed, the remaining strength of those members reduces along with the structural stability of the building.

Various surveys have been conducted using a variety of different approaches to collect data on the movable fire load and density in residential properties in Canada, India and Hong Kong. No equivalent work has been undertaken in New Zealand. The method used in Canada (Bwalya et al., 2011) using real estate advertising data and a database of representative furniture items could be used in a New Zealand context to develop a dataset. It is considered that this data might under-represent the FLED that might be expected in a normal home due to staging and clearing up of extraneous items for the sale process.

In the absence of New Zealand-specific data, Appendix 1 of the *Fire Safety Journal*, Volume 10, Issue 2, 1986 contains tables of FLED data collected from various European and US datasets. Although a specific distribution is not identified, the tables provide average and standard deviations across different occupancy types.

Table A.5 of PD 7974-1 (BSI, 2019b) provides some distributions for a variety of occupancy types, referencing data from Schleich and Cajot (2001), Zalok, Hadjisophocleous and Mehaffey (2009) and also the *Fire Safety Journal* discussed above.

3.1.4 Species production

In the VM, Table 2.1 (reproduced above as Table 2) identifies four chemical species produced as a result of pre-flashover combustion: soot (Y_{soot}), carbon monoxide (Y_{CO}), carbon dioxide (Y_{CO2}) and water (Y_{H2O}). It also defines the change in heat of combustion (ΔH_C). The values in the table are deterministic rather than a distribution of the likely species produced, and also they do not necessarily account for the changes in species production over time. For example, there is no consideration of the insipient phase where a fire might smoulder for a significant amount of time prior to ignition. The VM further defines the post-flashover values of Y_{soot} as 0.14 kg/kg$_{fuel}$ and Y_{CO} as 0.40 kg/kg$_{fuel}$. The commentary states that data is drawn from the SFPE Handbook and BRANZ Study Report No. 185. Although it does not specify which edition of the SFPE Handbook, the 4th edition is listed in the references.

Species production is highly dependent upon the material being burnt and the available oxygen, i.e. the ventilation conditions.

Hou (2011) analysed data from Tewarson (2002), Mulholland (2002), Robbins and Wade (2008), Wade and Collier (2004) and Young (2007) to determine statistical distributions for yields of CO, CO_2 and soot. Where data was available, Hou was able to determine the species yields at different stages of the fire development (growth, transition and smouldering). The results are grouped into similar products – for example, wall board tests, carpet tests and furniture tests containing polyurethane foams.

Species yield from both the building and its contents is something that is currently being scoped at BRANZ in a study co-funded by FENZ. Modern materials have the potential to evolve other species that are toxic at much lower exposure levels than CO or CO_2 and at different times during the development of the fire, although the quantities produced relative to CO and CO_2 are not clear. Further research around the time and distribution of species production through the development of a range of fire scenarios would provide a better risk-informed solution.

3.1.5 Compartment geometry

Compartment geometry will affect the smoke layer development and height and is therefore a driver for the tenability conditions. Usually, the geometry of the building being verified would already be known, so a statistical distribution of compartment geometry would not be required. However, there may be design scenarios where the compartment size could be adjusted to meet the requirements for a given RSET/ASET.

In this case, the distribution would not be a statistical distribution but a set of limits to define the maximum dimensions of the compartment.

3.1.6 Ventilation conditions

The ventilation conditions affect the growth rate of the fire as discussed in section 3.1.1 and the potential toxic species produced as discussed in section 3.1.4.

The VM sets out modelling rules in section 2.2.1 and includes a number of rules relating to the ventilation conditions in sub-paragraphs b) to m).

3.1.6.1 Fire and smoke control doors

Fire and smoke control doors (tested to a recognised national or international standard) are assumed to be closed unless being used by an occupant for egress. If the occupant load is low, the door is considered to be open for 3 seconds per occupant. If the occupant load is high and queuing is expected, the door is considered to be open for the duration of the queuing.

Sub-paragraph 2.2.1 c) of the VM states: "Smoke control doors serving bedrooms in sleeping areas where care is provided (these do not have self-closers) shall be considered to be closed from the time that evacuation from the bedroom is completed." This statement would appear to be contrary to the scope of the VM, which specifically excludes facilities such as hospitals and care homes under paragraph 1.2.1 Comment 3.

Sub-paragraph 2.2.1 f) states: "Doors being used for egress, when in the open position, are assumed to be half-width for smoke flow calculations." The commentary says that this is based on the fact that the door is unlikely to be fully opened and is also partially obstructed by the occupant during egress, reducing the effective ventilation area.

Frank, Spearpoint and Weddell (2014) undertook a study of 52 fire doors in a variety of multi-occupancy settings, including hotels, apartments and care facilities, over a period of 180 days to assess the statistical probability that the door would be open. They determined that the probability that a door would be open is an inverse Gaussian distribution with a mean 0.104 with a shape factor 0.0117. The data showed that, although most doors were closed most of the time, some doors were propped open for long periods. This is not consistent with the VM.

3.1.6.2 External doors

Sub-paragraph 2.2.1 d) of the VM specifies that, unless specifically designed to be open in the event of a fire, external doors and closures such as roller shutters should be modelled as closed. This might be dependent upon the building use. For example, small manufacturing or storage facilities might operate regularly with roller shutters in the open position to allow for easy loading/unloading of deliveries. These are not specifically designed to be open in the event of a fire but could potentially be open. Further investigation would be required to provide a probabilistic distribution of whether a particular type of door might be open or not.

3.1.6.3 Other doors

All internal, non-fire-rated doors are considered to be open unless a substantiated functional reason' has been identified in the fire engineering brief (FEB).

Further work similar in nature to the study carried out by Frank, Spearpoint and Weddell (2014) would be required to determine the likelihood of non-fire-rated internal doors being open or closed. Even though the doors are not fire or smoke rated, they would still slow the spread of smoke and other toxic products away from the room of origin. Given that this type of door is not normally fitted with a closer, the position of the door after an occupant has gone through while egressing would need to be considered.

3.1.6.4 Fire-rated construction

In accordance with the VM, fire-rated construction is considered to have no leakage. This is considered unlikely, but further work would be required to support a change to this parameter.

3.1.6.5 Non-fire-rated construction

Non-fire-rated construction is assumed to have a leakage equal to 0.1% for lined walls (internal or external) and 0.5% for unlined external walls. Further work would be required to validate these assumptions, especially considering the drive to more airtight construction for energy efficiency.

3.1.6.6 Glazing

Fire-rated glazing is expected to stay in place up to the rated time. Given its construction (generally interlayers between the glass), it is unlikely that the glazing is going to fall out completely as soon as the rated time is exceeded. Further work would be required to provide a statistical distribution of the likelihood of the glazing failing and the extent of fallout contributing to the ventilation of the fire.

Non-fire-rated glazing is assumed to break (and fall out to become completely open) at the sooner of either the upper smoke layer temperature reaching 500°C or the fire becoming ventilation limited. The commentary points out that most research into the fire performance of glazing has focused on if/when the glass will crack, not if/when the glass will fall out and, in addition, how much falls out. These factors will influence the contribution to the ventilation of the fire.

Wong, Li and Spearpoint (2014) conducted experiments with 117 samples of 4 and 6 mm single glazing in an aluminium frame with both standard rubber seals and non-standard ceramic-fibre seals. They analysed the time to glass failure and the percentage of glass lost due to falling out. In this manner, they produced a probabilistic model for percentage glass fallout against time after initial fracture of the glass. The method used does not account for the effects of pressure on the windows, either in the form of wind loading or the pressure caused by the thermal gradient, i.e. overpressure at the top and underpressure at the bottom.

The move to more thermally and acoustically efficient buildings is also driving the use of more double and triple glazing. Wang et al. (2017) conducted several small-scale studies looking at glass fracture and fallout, comparing coated single glazing, insulated double glazing and laminated glazing. Wang and Rush (2018) also studied the effects of fire on tempered glazing and determined that, although they are up to four times more resistant to the effects of fire, when the glass crack was initiated, the whole window was lost within 1 second. This was unlike conventional float glass, which showed much less fallout after cracking was initiated (Wang et al., 2017).

There is no allowance in the rules for windows that could be open – for example, as a result of seasonal effects and occupant behaviour – which therefore contribute to ventilation of the fire in the early stages even before the glazing is assumed to crack and fall out.

3.2 Tenability limits

The design fire parameters along with the compartment geometry are used to calculate the tenability limits and therefore the ASET. The VM requires that the tenability limits are measured at 2.0 m above the floor. Ministry of Health data shows the average height for New Zealand males is currently 1.76 m and 1.63 m for women (MoH, 2018). Consequently, the height used for calculating the tenability limits would again appear to be a conservative value.

It is also considered by the author that it is unlikely that occupants would remain upright if the smoke layer was to descend below 2 m, therefore reducing exposure to the heat and toxic gas species. Further work would be required to verify and quantify this aspect.

Three tenability limits are defined within the VM: visibility, fractional effective dose of thermal conditions ($FED_{thermal}$) and fractional effective dose of toxic species, generally lumped into an equivalent exposure to carbon monoxide (FED_{CO}).

It is considered most likely to be the visibility limit that is exceeded first. Although visibility is not likely to be the cause of death, it is linked directly to an occupant's ability to get out of a compartment before exposure to heat and/or other toxic products that might kill.

The VM states that, to provide consistency in the output, the methodology in ISO 13571 should be used to calculate both $FED_{thermal}$ and FED_{CO}. However, ISO 13571 also calculates the fractional irritant concentration (FIC) and the effect that irritant gases have on the ability of an occupant to safely get out. The effects of irritant gases on parameters such as walking speed are not considered in the VM.

3.2.1 Visibility

The visibility limit is a measure of the smoke level within a compartment and thus an indicator of an occupant's ability to navigate successfully out of the compartment. The smoke layer thickness is normally determined using a numerical model – either a CFD-based model such as FDS or a zone model such as B-RISK. The visibility limits defined in NZBC clause C4.3(c) are 10 m for rooms of >100 m^2 and 5 m for rooms of <100 m^2 unless, in accordance with clause C4.4, no more than 1000 occupants can be exposed in a firecell that is fitted with an automatic sprinkler system.

It is unclear from the VM or the commentary where the visibility limits have been derived from, but they would appear to align with Purser (2008).

There are also circumstances where the visibility might drop below the minimum required for short periods of time and then return to an acceptable level – for example, when occupants open a door to enter a stairwell. In this situation, visibility may drop but then recover when the door is closed again. This is often referred to as a 'blip' but is currently not accounted for in the NZBC. Further work would be required to understand the extent and acceptable length of a 'blip' for a design to be considered compliant.

3.2.1.1 Smoke separations

Smoke separations are there to prevent the spread of smoke and toxic species from the fire compartment to the rest of the building.

Modelling rules applied in the VM in paragraph 2.2.1 state that, if a smoke separation complies with a national or international standard, it is assumed to remain in place up to the rated temperature or the time at which flashover occurs, whichever is sooner. Smoke separations that are not of fire-rated construction (but imperforate) are assumed to stay in place until the upper layer smoke temperature reaches 200°C.

Further work would be required to quantify the likelihood of the smoke separations staying in place and the extent of failure.

3.2.2 $FED_{(thermal)}$

An $FED_{(thermal)}$ equal to 1.0 is the combined dose of convective and radiated heat that would render a person of average susceptibility incapable of escape (ISO, 2012). NZBC clause C4.3(b) requires that the design can demonstrate an escaping occupant is exposed to an $FED_{(thermal)}$ of not greater than 0.3 unless, in accordance with clause C4.4, no more than 1000 occupants can be exposed in a firecell that is fitted with an automatic sprinkler system.

The exposure to convective and/or radiant heat will be dependent upon the conditions along a given escape path. FED is therefore calculated cumulatively. The commentary states that the interval between calculations should not exceed 5 seconds.

3.2.2.1 Radiant heat

According to ISO 13571, skin exposure to <2.5 $kW.m^{-2}$ radiant heat flux can be tolerated for 30 minutes or more without significantly affecting the occupant's ability to escape. Beyond 2.5 $kW.m^{-2}$, the time for the onset of pain and second-degree burning of the skin t_{Irad} reduces rapidly.

The reciprocal of the t_{Irad} gives the accumulated FED per minute. Where the heat flux is <2.5 $kW.m^{-2}$, this can be factored out to zero in the overall FED calculation (Equation 11 in ISO 13571).

The equations given in ISO 13571 for second-degree exposed skin burns (Equation 7) and onset of pain (Equation 8) are estimated to have an uncertainty of ±25%.

3.2.2.2 Convective heat

According to ISO 13571, the time to incapacitation (as a result of exposure to convective heat containing less than 10% by volume of water vapour t_{Iconv}) is dependent upon whether the occupant is clothed or not and provides equations for both.

The reciprocal of the t_{Iconv} gives the accumulated FED per minute.

The equations given in ISO 13571 for convective heat exposure when clothed (Equation 9) and unclothed or lightly clothed (Equation 10) are estimated to have an uncertainty of ±25%.

3.2.3 $FED_{(CO)}$

An $FED_{(CO)}$ equal to 1.0 is the equivalent dose of carbon monoxide that would render a person of average susceptibility incapable of escape (ISO, 2012). NZBC clause C4.3(a) requires that an escaping occupant is exposed to an $FED_{(CO)}$ of not greater than 0.3.

At present, the distribution of human response to fire gases is unknown. ISO 13571 assumes a log-normal distribution, therefore an FED of 0.3 equates to 11.4% of the general population being susceptible to concentrations below that specified. This might not be the case if applied to a more vulnerable population.

The exposure to carbon monoxide will be dependent upon the conditions along a given escape path. FED is therefore calculated cumulatively. The commentary states that the interval between calculations should not exceed 5 seconds.

The VM specifies, $FED_{(CO)}$ to be calculated in accordance with ISO 13571 but does not include effects of other toxic and irritant gases.

3.3 Required safe egress time (RSET)

RSET is defined in the VM in Equation 3.1:

$$RSET = (t_d + t_n + t_{pre}) + (t_{trav} \text{ or } t_{flow})$$

where:

t_d = the detection time, determined from deterministic modelling

t_n = the time from detection to notification of the occupants

t_{pre} = the time from notification until evacuation begins

t_{trav} = the time spent moving towards a place of safety

t_{flow} = the time spent in congestion controlled by flow characteristics

3.3.1 Detection time

Detection time (t_d) is a function of the sensing element response time index (RTI), the ceiling jet flow velocity and the plume temperature. The ceiling jet flow velocity and plume temperature must be known with respect to time, which is normally determined using a CFD or zone model.

The ceiling jet flow and plume temperature are a function of the design fire selected and will be determined by the geometry of the space (which is considered to be known values and therefore no uncertainty), the FLED, the fire growth rate and the ventilation, which would be distributions of possible parameters.

RTI is given in Table 3.2 of the VM as 30 $m.s_{1/2}$ for heat detectors, 135 $m.s_{1/2}$ for standard response sprinklers and 50 $m.s_{1/2}$ for extended coverage and fast-response sprinklers.

Work by Tsui and Spearpoint (2010) investigated the uncertainty associated with sprinkler RTI and C factor. @Risk was used to classify the distributions. However, there was little consistency across sprinkler types when the distributions were classified. The first ranked distributions for standard response sprinklers included Weibull, normal and logistic, and the distribution varied dependent upon sprinkler orientation in the test apparatus. Similar results were observed for fast-response sprinklers.

Without testing all possible sprinkler types, it is considered that single RTI distribution would not adequately describe the variability. However, if the type of sprinkler head being used was known and tested, a suitable distribution for that head could be used. Furthermore, Frank, Spearpoint, Fleishman and Wade (2011) determined through a sensitivity analysis that RTI and C factor were relatively insensitive, with fire growth rate having the greatest effect on time to activation.

RTI for heat detector systems is specified in Table 3.2 of the VM as 30 m.s$^{1/2}$. However, there is no indication in the commentary as to where the RTI figures have been derived from. The activation temperature T_{act} is also defined as 57°C.

It is not clear if the figure takes into account modern semiconductor-based sensors, which are able to trigger upon on rate of change of temperature rather than just a fixed threshold level.

3.3.2 Notification time

Notification time (t_n) is defined in the VM in paragraph 3.2.2 as 30 s as the standard, with an allowance for extended notification times for non-standard evacuation strategies (for example, management investigation of sole activations). It is unclear from the commentary where this value was obtained from. The VM also specifically states that, regardless of the system specified, the minimum value of 30 s shall be used. If the system to be installed has been characterised, the notification time should be determined and therefore it would not be necessary to have a probabilistic distribution of the parameter.

3.3.3 Pre-travel time

Pre-travel time is defined in the VM in Table 3.3. This is based upon whether or not the occupants are awake and familiar (or not) with the building. There are also pre-travel times defined for cases where buildings are occupied by patients under care of specialist staff and are awake or not. The values defined in the VM are closely aligned with PD 7974-6 (BSI, 2004) as shown in Table C2 of the commentary. Allowances have been made in the VM for the fact that occupants in the location of the fire, once alerted by an alarm signal (voice or standard), will have additional visual cues from the fire and therefore start to evacuate sooner.

The pre-travel times in Table C.1 of PD 7974-6 are given for the 1st and 99th percentile occupants to move. However, the time given for the 99th percentile is not the absolute time from being alerted – it is the additional time taken over the 1st percentile. The total absolute time is given by the sum of the 1st and 99th percentile columns as indicated by a note at the bottom of the table. This is not clear in the VM and could result in less-conservative times being used. The data used for the development of BS 7974 (BSI, 2019a) and its Published Documents could form the basis of probabilistic distributions for use in a risk-based approach as the data is about an individual’s time to respond and not dependent upon any country-specific building code. BS 7974 and its associated Published Documents (PD1–PD7) have recently been updated. Annex E of PD7974-6 (BSI, 2019c) contains more detailed distribution data from a range of actual fires and reports minimum, 1st quarter, median, 3rd quarter, max and mean times where data is available.

Lovreglio et al. (2019) expanded on the database presented in the SFPE Handbook. They provide distributions of pre-travel time broken down by occupancy type, but they also undertook a cluster analysis on each occupancy type in an attempt to provide fire safety engineers with a range of distributions that could be applied to different scenarios. However, some of the clustering appears arbitrary based on usage. For example, Cluster 5 – Lecture Halls in the Educational Occupancy clearly has two distinct distributions but have been combined to give a single curve, with the resulting R_2 only 0.53. Further work should be undertaken to understand the factors driving the spread in nominally similar occupancies.

There is also anecdotal evidence, supported by Sesseng, Storesund and Steen-Hansen (2019) of RISE Fire Research AS in Norway, presented during the Interflam 2019 conference. Following a very large industrial fire in Norway, the investigation showed that there were significant delays in occupant pre-movement times as a result of numerous false alarms leading up to the fire.

Pre-travel time also includes the time taken to wake from sleep. Ball and Bruck (2004) demonstrated the effects of alcohol on sleeping occupants and showed that, with even a relatively low blood alcohol concentration (BAC) of 0.05, over 36% showed no response below 95 dBA or, worse still, no response at all.

3.3.4 Travel time

Travel time is the time spent moving to a 'place of safety'. A place of safety can be outside the building or inside the building in an area isolated from the effects of the fire. However, C/VM2 is limited in scope to buildings that evacuate immediately outside the building. The travel time is the greater of the time taken to travel to the doorway of a compartment or the flow time – the time required for all of the occupants of a compartment to pass through a restriction such as a doorway when queuing is required – and is calculated in the VM using Equations 3.2 to 3.4.

3.3.4.1 Time to get to doorway

Parameters for calculating the travel speed in Equation 3.2 are given in Table 3.4 of the VM (reproduced below as Table 4) and are limited to a maximum travel speed of 1.2 m/s. The travel time is then calculated by dividing the distance travelled by the travel speed. Table 3.4 provides factors to apply to Equation 3.2 depending upon whether the travel is horizontal or includes stairs with a variety of tread and riser sizes but does not allow for different travel speeds by different sectors of the community, i.e. children or the elderly. Some data has been collated in the 5th edition of the SPFE Handbook (SFPE, 2016) in Chapter 64 Engineering Data. However, the author states that the data has been collated from a number of different sources and care should be exercised in use of the data to understand the context in which it has been collected. The data provides deterministic speeds or ranges of speeds rather than statistical distributions. Distributions of walking speeds across different occupant groups would be required.

Fridolf, Nilsson, Frantzich, Ronchi and Arias (2018) analysed data from Frantzich and Nilsson (2003), Akizuki et al. (2007), Fridolf et al. (2013; 2015) and Seike et al. (2016) and Jin's (1976) non-irritant smoke data. Rather than a statistical distribution, Nilsson suggests that, beyond 3 m visibility, walking speed in unaffected by smoke, and below 3 m, there is a linear decrease in walking speed of 0.34 m/s per metre reduction in visibility down to 0.2 m/s.

Table 4. C/VM2 travel speed parameters (Table 3.4 extracted from C/VM2).

Table 3.4 **Maximum flow rates for use in equation 3.2 for horizontal and vertical travel speeds**

Exit route elements		k	Speed m/s
Corridor, aisle, ramp, doorway		1.40	1.2
Stair riser (mm)	Stair tread (mm)		
191	254	1.00	0.85
178	279	1.08	0.95
165	305	1.16	1.00
165	330	1.23	1.05

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Travel speed may also be affected by other factors such as visibility, physical ability and wayfinding decisions.

Jin (1976) showed that walking speed was proportional to visibility and that the effects were amplified when the reduction in visibility was as a result of irritant smoke. Jin derived formulae for calculating walking speed for both irritant and non-irritant smoke conditions. However, these are still determinate values rather than probable distributions.

Wayfinding decisions can be affected by numerous factors, including visibility, with 30% of people deciding to turn back rather than enter a smoke-logged compartment with a visibility of less than 3 metres (Purser, 2008). Smoke also has the effect of reducing light levels. With conventional lighting and escape signage being located high up, smoke would obscure these. Perhaps lessons could be learned from the aviation industry where escape path lighting is provided at floor level where it is not obscured by smoke.

Wayfinding decisions can also be affected by the type of occupancy and the likely impairment of the occupants – for example, night clubs where the bulk of the occupants may be under the influence of alcohol and/or drugs. Further work would be required to fully quantify the effects.

3.3.4.2 Flow time

To calculate the flow rate in Equation 3.4 of the VM, the occupant density at the constriction must be known and 1.9 persons/m_2 is given as an example for a doorway. The effective width is given by subtracting the boundary layer thickness on each side, as given in Table 3.5 of the VM (reproduced below as Table 5). The flow rate through a door leaf is limited to 50 persons/min if a self-closing device is fitted but is unlimited otherwise. The VM refers the reader to the 4th edition of the SFPE Handbook (SFPE, 2008), Section 3, Chapter 13 for more information regarding egress calculations.

The 1.9 persons/m_2 occupant density at the constriction is given as an example in the VM, and this is in agreement with the SFPE Handbook. The SFPE Handbook also states that higher occupant densities can occur but result in slower egress rates and therefore should not be used for engineering design. However, to assume the best-case flow rate for occupants may produce an overly optimistic RSET time.

Table 5. C/VM2 boundary layer width (Table 3.5 extracted from C/VM2).

Table 3.5	**Boundary layer width for calculating the effective width of an exit component**
Exit route element	Boundary layer on each side (m)
Stairway – walls or side tread	0.15
Railing or *handrail*	0.09
Theatre chairs, stadium bench	0.00
Corridor wall and ramp wall	0.20
Obstacle	0.10
Wide concourse, passageway	0.46
Door, archway	0.15

Total occupant density for a building is calculated based on the occupancy type and the floor area using Table 3.1 in the VM (reproduced below as Table 6 below). However, this is a deterministic value, and further investigation would be required to determine the likely occupant densities for different occupancy types and their associated statistical distributions.

Table 6. C/VM2 occupant density (Table 3.1 extracted from C/VM2).

Table 3.1 Occupant densities	
Activity	**Occupant density (m²/person)**
Aircraft hangars	50
Airports – Baggage handling area – Waiting/check-in – Terminal spaces	2 1.4 10
Area without seating or aisles	1.0
Art galleries, museums	4
Bar sitting areas	1.0
Bar standing areas	0.5
Bleachers, pews or bench type seating	0.45 linear m per person
Bedrooms	As number of bed spaces and staff when appropriate
Bunkrooms	
Dormitories, hostels	
Halls and *wharenui*	
Wards in hospitals, operating theatres and similar	
Detention quarters	
Boiler rooms, plant rooms	30
Bulk storage including racks and shelves (warehouses etc)	100
Call centres	7
Classrooms	2
Commercial kitchens	10
Commercial laboratories, laundries	10
Computer server rooms	25
Consulting rooms (doctors, dentists, beauty therapy)	5
Dance floors	0.6
Day care centres	4
Dining, restaurant and cafeteria spaces	1.25
Early childhood centres	Based on Education (Early Childhood Services) Regulations 2008 plus the number of staff
Exhibition areas, trade fairs	1.4
Fitness centres	5
Gaming and casino areas	1
Heavy industry	30
Indoor games areas, bowling alleys	10
Interview rooms	5
Libraries – stack areas	10
Libraries other areas	7
Lobbies and foyers	1

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Table 3.1	Occupant densities (continued)
Activity	Occupant density (m^2/person)
Mall areas used for assembly uses	1
Manufacturing and process areas	10
Meeting rooms	2.5
Offices	10
Parking *buildings*, garages	50
Personal service facilities	5
Reading or writing rooms and lounges	2
Reception areas	10
Retail and trading (with storage >3.0 m high) (eg trading stores and supermarkets)	5
Retail spaces and pedestrian circulation areas including malls and arcades	3.5
Retail spaces for furniture, floor coverings, large appliances, building supplies and Manchester	10
Showrooms	5
Spaces with fixed seating	As number of seats
Spaces with loose seating	0.8
Spaces with loose seating and tables	1.1
Sports halls	3
Stadiums and grandstands (standing areas)	0.6
Staffrooms and lunch rooms	5
Stages for theatrical performances	0.8
Standing spaces	0.4
Swimming pools: water surface area	5
Swimming pools: surrounds and seating	3
Teaching laboratories	5
Technology class rooms in schools (eg wood work, metal work)	10
Workrooms, workshops	5

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4. Summary

A literature review was undertaken to identify parameters in the New Zealand Building Code and Verification Method C/VM2 that would require statistical distributions to form the basis of a risk-informed fire safety design.

A wide range of parameters were identified, some of which had been investigated previously and have statistical distributions available and others that do not. The parameters investigated fall into three main areas: those required for calculating the available safe egress time (ASET), the tenability limits for occupants and the required safe egress time (RSET). The main parameters included fire growth rate, heat release rate, fire load energy density, species production, ventilation conditions and movement times.

Table 7 contains a summary of the parameters identified along with the current deterministic values, identified distributions and where further work is required to identify distributions.

Further work will be required to identify statistical distributions for parameters not yet classified at this time. That said, probably of greater importance would be a sensitivity analysis to determine which of these identified parameters have the greatest influence on the outcome of engineering analyses. In this way, research can be focused on the key parameters required and the greatest research impact can be targeted.

Table 7. Summary of current and proposed parameter values.

Parameter	Current value in NZBC C/VM2	Proposed distribution reference
Fire Service response time	Not specified	Claridge and Spearpoint (2013)
Fire growth rate	Table 2.1	Nilsson et al. (2014)
Heat release rate	Table 2.1	Limited data from Young (2007), further work required.
Fire load energy density	Table 2.2	PD7974-1 (BSI, 2019b), further work required for data with a New Zealand context
Species yield (CO, CO_2 and soot)	Table 2.1	Hou (2011)
Fire/smoke control doors	Closed	Frank et al. (2014)
External doors/shutters	Closed unless specifically designed to be open	Further work required
Other doors	Open	Further work required
Fire-rated construction	No leakage	Further work required
Non-fire-rated construction	0.1% for lined internal or external walls 0.5% for unlined external walls	Further work required
Fire-rated glazing	Expected to remain in place up to the rated time	Further work required
Non-fire-rated glazing	Assumed to remain in place up to the point at which either the upper hot gas layer exceeds 500°C or the fire becomes	Wong et al. (2014), Wang et al. (2017), Wang and Rush (2018) Further work required to quantify the likelihood of breakage and

Parameter	Current value in NZBC C/VM2	Proposed distribution reference
	ventilation limited, at which time it is assumed to fall out completely	the extent of fallout of different types of glazing under normal fire conditions, taking into account pressure and wind loading
Height for tenability limits	2 m	Further work required to determine a distribution of New Zealand population height, based on Ministry of Health data and the likelihood that occupants would crouch down to avoid the hot smoke layer
Visibility	10 m for rooms >100 m^2 5 m for rooms <100 m^2	Further work required to quantify the effects of a 'blip' in visibility
Fire-rated smoke separations	Assumed to stay in place up to the rated temperature of the time at which flashover occurs	Further work required to quantify the likelihood and extent of failure
Non-fire-rated smoke separations (but imperforate)	Assumed to stay in place until the upper smoke layer reaches 200°C.	Further work required to quantify the likelihood and extent of failure
FED (thermal and CO)	Calculated in accordance with ISO 13571 (ISO,2007)	ISO 13571 accounts for a statistical distribution of susceptibility with the limit set in the NZBC (0.3) equating to 11.4% of the population being susceptible to lower exposures
Sprinkler response time index (RTI) and C factor	Table 3.2	Tsui and Spearpoint (2010), although a sensitivity analysis showed fire growth rate to have the greatest effect on sprinkler activation time
Heat detector activation temperature	57°C	Further work required to quantify the sensitivity of rate-of-change heat detection systems
Notification time	30 s Extended for non-standard evacuation strategies	Dependent upon the system selected
Pre-travel time	Table 3.3	PD7974-6 (BSI, 2019c)
Walking speed	1.2 m/s	Nilsson (2018) provides a range of walking speeds but does not include the effects of irritant smoke; further work required including determining statistical distributions for vulnerable populations

Parameter	Current value in NZBC C/VM2	Proposed distribution reference
Travel time	Table 3.4	Table 3.4 gives equations to be used to calculate travel time based on distance and walking speed but does not include any wayfinding effects where an occupant may be unfamiliar with the building; further work required
Flow time	1.9 persons/m^2 is suggested for Equation 3.4 of the VM using Table 3.5 for the boundary layer width	Further work required to get a distribution of occupant density at the constriction
Occupant density	Table 3.1	Further work required to determine probabilistic distributions for the occupant density based on occupancy type

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