Towards a risk-informed approach to fire-safety design

The New Zealand Building Code (NZBC) and Verification Method C/VM2 help ensure that a building design complies with criteria for fire safety. However, the values given as parameters in the NZBC and C/VM2 do not account for risk, and some may be conservative estimates. BRANZ undertook an international literature review on technical justifications for these parameters and to find representative statistical distributions, where available. Incorporating statistical distributions could support a more risk-informed design output, but further work is needed to understand and constrain many of these values and distributions.

The criteria for fire safety in the NZBC are found in clauses C1 to C6 *Protection from fire* (Table 1) along with clause A3 *Building importance levels*. The NZBC is performance-based, meaning that, if a design meets the criteria, building consent authorities must accept it.

Table 1. Objectives of clauses C1–C6 *Protection from fire.*

CLAUSE	OBJECTIVE
C1	Objectives of clauses C2 to C6 (Protection from fire): sets out safety objectives for people, other property and firefighting.
C2	Prevention of fire occurring: specifies safeguards against illness or injury due to fire and requirements for the design, construction and installation of controlled combustion and other fixed fire equipment.
C3	Fire affecting areas beyond the fire source: requires that design and construction means low risk of injury or illness to people not close to a fire and specifies requirements against vertical or horizontal fire spread and performance criteria to be met by certain materials in certain situations.
C4	Movement to place of safety: specifies requirements for fire warning systems, visible escape routes, conditions for evacuation time and provisions for automatic fire sprinkler systems.
C5	Access and safety for firefighting operations: specifies appropriate access and safety measures including hazards information and inlets for automatic fire sprinklers and hydrant systems.
C6	Structural stability: requires structural systems that allow firefighters safe access to floors before, during and after a fire and protect building elements with lesser fire resistance from collapse.

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Verification Method C/VM2 is one of the ways that building designers can demonstrate NZBC compliance for fire safety for some building types. Using this method, building designers must show how the proposed building will perform under 10 scenarios (Table 2), each representing a different aspect of fire performance. Many of these criteria require analysis or a calculation to demonstrate compliance.

The spread of fire in a building is difficult to predict with any certainty due to the large number of variables involved and their uncertainties. The documentation supporting C/VM2 also cautions that it:

"... 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 [historical] values within all of the international codes that are commonly accepted but have no technical basis."

There is a risk that the values defined in the NZBC and C/VM2 are too conservative. These may lead to an overly conservative design

Table 2. C/VM2 design scenarios (Table 1.1 extracted from C/VM2 page 24).

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

where the cost of protection measures might be disproportionate to the level of risk.

Using a risk-informed design process could account for some of this uncertainty by incorporating data distributions based on probability rather than absolute deterministic values in the modelling.

BRANZ reviewed the current rules and identified the relevant parameters in the NZBC, C/VM2 and commentary documentation supporting C/VM2. A literature review was undertaken to find technical justifications for the values of these parameters. The research also identified which parameters would need a representative statistical distribution. Applying these as inputs to any modelling could provide a more risk-informed design output.

A wide range of parameters was identified, some of which had already been investigated and have statistical distributions available and others that do not. The parameters included fire growth rate, heat release rate, fire load energy density, species production, ventilation conditions and movement times and fall into three main areas:

- Parameters required for calculating the available safe egress time (ASET).
- The tenability limits for occupants.
- The required safe egress time (RSET).

BRANZ first looked into the requirements specified in the NZBC and then those required in C/VM2.

Parameters set in the NZBC

It is generally accepted that it is the role of the regulator to define an acceptable level of individual and societal risk either in the NZBC or the associated compliance documents.

However, research by BRANZ found that many clauses within the NZBC require a "low probability" of an occurrence, without defining what an acceptable low probability is.

Clause C1 – requirements for risk

Clause C1 defines the objectives that clauses C2 to C6 must achieve to provide protection from fire in buildings. These 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.

Although the first objective refers to "unacceptable risk", the NZBC does not define or quantify this level of risk.

Clauses C3.2 and C3.5 – spread of fire between floors and over external cladding

Clause C3 gives the general requirements for controlling the spread of fire both horizontally and vertically from sources inside and outside the building.

Clause C3.2 requires that buildings over 10 metres high and used for sleeping or any other property with importance level greater than 1 "must be designed and constructed so that there is a low probability of external fire spread to upper floors in the building".

Clause C3.5 specifies that fire must not spread more than 3.5 m vertically from the fire source over the external cladding of the building.

Neither clause C3.2 or C3.5 include a rationale for these figures, and in clause C3.2, it is not clear whether the 10 metres is measured to wall height, roof height or escape height (floor height on the uppermost level).

A number of alternative internationally recognised test standards and methodologies are available to demonstrate compliance with the requirement to limit the spread of fire over the surface cladding of a building, but none can be used to directly demonstrate compliance with the criteria in clause C3.5.

Clause C3.4(b) – spread of fire over floor coverings

Clause C3.4(b) specifies the minimum critical radiant flux (CRF) for floor coverings in areas of a building depending on whether sprinklers are fitted or not.

The C/VM2 commentary contains no analytical support for the values selected but refers to the Building Code of Australia, which has the same values with slightly different criteria.

Clauses C3.6 and C3.7 – spread of fire to adjacent properties

Clauses C3.6 and C3.7 limit the spread of fire to and from adjoining properties. Clause C3.6 specifies the emitted radiant heat flux limit at the boundary (30 kW/m^2) and at 1 metre beyond the boundary (16 kW/m^2), while clause C3.7 restricts the combustibility of materials used in boundary walls located closer than 1 m from the relevant boundary.

The exposure time for clause C3.7 is dependent upon the building importance level.

- Importance levels 1 and 2 buildings (low or normal risk to life or the environment or low to normal economic cost should the building fail) must not ignite within 15 minutes when exposed to a received radiant heat flux of 30 kW/m^2
- Importance level 3 buildings (higher level of societal benefit or importance or higher levels of risk to building occupants) or importance level 4 buildings (essential to post-disaster recovery or associated with hazardous facilities) must not ignite within 30 minutes when exposed to a received radiant flux of 30 kW/m^2.

The C/VM2 commentary contains rationale for the lower limit of 16 kW/m^2 beyond 1 metre from the boundary but does not provide any basis for selecting this value.

Clause C3.8 – large buildings without sprinklers

Clause C3.8 deals with large buildings without sprinklers within 15 m of a boundary. Where the floor area of the fire cell 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 the time it took to detect the fire and the time it took FENZ to respond and set up. Response times to structure fires are variable and are based on the location of the incident (urban/rural/metropolitan).

It is not clear from the C/VM2 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 FENZ 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'.

Clause C4.3 – maintaining tenable environments and safe egress

Clause C4.3 defines the requirements for maintaining a tenable environment within the building and to allow the safe egress of occupants. Clause C4.3(a) sets the maximum level of carbon monoxide exposure to an occupant at 0.3 fractional effective dose (FED), and clause C4.3(b) sets the maximum heat exposure to an occupant at 0.3 FED. Clause C4.3(c) also defines the minimum visibility as a result of smoke obscuration.

Fractional effective dose (FED)

- ISO 13943 defines FED as the ratio of the exposure dose for an asphyxiant to the exposure dose expected to produce a specified effect on an exposed subject of average susceptibility.
- ISO 13571 defines FED in terms of incapacitation - an FED of 1.0 is the relative dose of an asphyxiant required to leave the average person unable to escape unaided.

The C/VM2 commentary acknowledges that there is considerable uncertainty due to limited data on the physiological effects of contaminants but that an FED of 0.3 should correspond to approximately 11% of the population being susceptible to the intoxicating effects and therefore unable to effect their own escape.

Clause C4.3(c) defines the minimum visibility as a result of smoke obscuration. Visibility must not reduce to less than 10 m except in rooms of less than 100 m², when visibility may fall to 5 m.

C/VM2 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.

Input parameters for calculations for C/VM2

C/VM2 specifies expected methods for demonstrating compliance including calculating the available safe egress time (ASET) versus the required safe egress time (RSET) and tenability limits. Parameters must also be set for the design fires used.

BRANZ undertook a literature review to find technical justifications for the values of these parameters and their representative statistical distributions, which are summarised in Table 3.

Recommendations

- Before a risk-informed approach to fire-safety design in buildings can be developed, further research is needed to determine statistical distributions for many of the parameters in the NZBC and C/VM2.
- Before embarking on further work, a sensitivity analysis should be carried out to find out which parameters have the greatest influence on the outcome of engineering analyses.
- Future research should focus on the key parameters to ensure the greatest research benefit.

More information

BRANZ Study Report SR430 *Preparing the foundation for risk-informed fire safety design*

Table 3. Summary of current and proposed parameter values in C/VM2 (see BRANZ Study Report SR430 for references).

PARAMETER	CURRENT VALUE IN C/VM2	PROPOSED PARAMETER VALUES AND DISTRIBUTION
FENZ response time	Not specified	The method to calculate the response time and distribution is given in Claridge and Spearpoint (2013).
PARAMETERS FOR CALCULATING ASET DESIGN FIRE		
Fire growth rate	Table 2.1	A rate of 0.047 kW/s² with a log-normal distribution would adequately describe 97% of accidental fires but only 91% of arson fires (Nilsson et al., 2014).
Heat release rate	Table 2.1	Limited data is available from Young (2007). Further work is required.
Fire load energy density	Table 2.2	PD7974-1 (BSI, 2019b) provides some distributions for a variety of occupancy types, but further work is required for the New Zealand context.
Species yield (CO, CO_2 and soot)	Table 2.1	Hou (2011) determined the species yields at different stages of the fire development (growth, transition and smouldering). Species yield from both the building and its contents 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.
PARAMETERS FOR DETERMINING ASET		
Fire/smoke control doors	Closed	Frank et al. (2014) 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 recommendation in C/VM2.
External doors/shutters	Closed unless specifically designed to be open	Further work is required.
Other doors	Open	Further work is required.

PARAMETER	CURRENT VALUE IN C/VM2	PROPOSED PARAMETER VALUES AND DISTRIBUTION
Fire-rated construction	No leakage	Further work is required.
Non-fire-rated construction	0.1% for lined internal or external walls; 0.5% for unlined external walls	Further work is required.
Fire-rated glazing	Expected to remain in place up to the rated time	Further work is required.
Non-fire-rated glazing	Assumed to remain in place up to the point at which either the upper hot gas layer exceeds 500ºC or the fire becomes ventilation limited, at which time it is assumed to fall out completely	Further work is required to quantify the likelihood of breakage and the extent of fallout of different types of glazing under normal fire conditions, taking into account pressure and wind loading – see Wong et al. (2014), Wang et al. (2017) and Wang and Rush (2018).
Height for tenability limits	2 m	Further work is 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.
PARAMETERS RELATED TO TENABILITY LIMITS		
Visibility	10 m for rooms >100 m^2; 5 m for rooms <100 m^2	Further work is 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 is 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 200ºC	Further work is required to quantify the likelihood and extent of failure.
FED (thermal and CO)	Calculated in accordance with ISO 13571	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.
PARAMETERS FOR DETERMINING RSET		
Heat detector activation temperature	57ºC	Further work is needed to quantify the sensitivity of rate-of-change heat detection systems.
Notification time	30 s; extended for non-standard evacuation strategies	This depends on the system selected.
Pre-travel time	Table 3.3	The data used for PD7974-6 (BSI, 2019c) and its published documents could form the basis of probabilistic distributions for use in a risk-based approach as the data relates to an individual's time to respond and is not dependent upon any country-specific building code.
Walking speed	1.2 m/s	Nilsson (2018) gives a range of walking speeds but does not include the effects of irritant smoke. Further work is required to include the statistical spread arising from vulnerable populations (e.g. the elderly, children and disabled people).
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 or when visibility is impaired or when wayfinding decisions are impaired (e.g. by smoke or if the occupants are under the influence of alcohol or drugs). Further work is required to calculate the likely statistical distribution in travel time.
Flow time	1.9 persons/m^2 is suggested for Equation 3.4 using Table 3.5 for the boundary layer width	The deterministic value in C/VM2 does not include a statistical distribution. Further work is required to understand the distribution of occupant density at this constriction.
Occupant density	Table 3.1	Further work is required to determine probabilistic distributions for the occupant density based on occupancy type.