Fire Safety Verification Method Data Sheets

Handbook annex

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Preface

The Inter-Government Agreement (IGA) that governs the Australian Building Codes Board (ABCB) places a strong emphasis on reducing reliance on regulation, including consideration of non-regulatory alternatives such as non-mandatory handbooks and protocols.

This Annex to the ABCB Fire Safety Verification Method Handbook includes Data Sheets to support the use of the *Fire Safety Verification Method* (FSVM).

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC *Deemed-to-Satisfy Provisions* (DTS) is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the *performance-based design brief* (PBDB).

Additional caution should be applied if any content of these Data Sheets is applied to an absolute analysis.

The version and date of each Data Sheet is indicated to facilitate continual updates to take account of feedback and the inclusion of more current and relevant data and methods as they become available. Readers are invited to submit suggestions for improvement including replacement / additional Data Sheets via the ABCB Online Enquiry webpage.

Contents

REMINDER

This document is not mandatory or regulatory in nature and compliance with it will not necessarily discharge a user's legal obligations. The document should only be read and used subject to, and in conjunction with, the general disclaimer at page i.

The document also needs to be read in conjunction with the relevant legislation of the appropriate State or Territory. It is written in generic terms and it is not intended that the content of the document counteract or conflict with the legislative requirements, any references in legal documents, any handbooks issued by the Administration or any directives by the *appropriate authority*.

GROUP B

DATA SHEETS

Data Sheet B1: Design Fires - Overview

Group B Data Sheets provide typical input data and guidance relating to the derivation of *design fires* and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

Use of information from Group B Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet (B1) provides a general overview of *design fires* and should be read in conjunction with the FSVM Handbook and other Group B Data Sheets which include:

- Data Sheet B2: Design fires - characteristic input data
- Data Sheet B3: Design fires - calculation methods for fully developed fires
- Data Sheet B4: Design fires – simple d*esign fires* for comparison of wall and ceiling linings

Design fires for Horizontal Fire Spread Between Buildings (HS) and Vertical Fire Spread (VS) scenarios are not addressed since these scenarios are predominantly addressed by *Verification Methods* CV1 to CV3.

Data Sheet B1 Contents

Version	Date	Data	Comments
B1-1	Dec 2018	B1	Final draft for comment
B1-2	Jun 2019	B1	Draft for publication

1.1 Derivation of Design Fires

1.1.1 General

Once the reference scenarios have been identified during the FSVM PBDB process it is necessary to derive appropriate *design fires* (quantified representations of fires within reference scenarios) to compare a proposed *Performance Solution* against the corresponding *reference building*.

The choice of reference scenarios and corresponding *design fires* may critically affect the outcomes of the *fire safety engineering* analysis and therefore it is important that due consideration is given to the derivation of *design fires*. This is not a straightforward task and the *design fire* needs to be appropriate to, amongst other things:

- the building / enclosure geometry and construction materials
- the reference scenario under consideration including the location of the fire, fire characteristics and impact of fire protection measures and other interventions
- the building use / building class which influences the *fire hazard* and response of occupants
- ventilation conditions
- the fire safety issues under consideration
- the analysis methods.

It is not the intention of the Group B Data Sheets to provide detailed guidance relating to the process of deriving *design fires* since there are many recently published standards and other technical documentation that provide guidance. Some of the most relevant standards and documents are listed below:

(a) The International Fire Engineering Guidelines (Chapters 2.3 and 2.4)[2] provides general guidance.

(b) The Practice Note for Design Fires prepared by Engineers Australia Society NSW Branch 2012 [3] provides more detailed guidance and is intended to supplement the International Fire Engineering Guidelines.

(c) ATS 5387.2-2006 Australian Technical Specification; Guidelines -Fire Safety Engineering Part 2: Design fire scenarios and design fires [4] which was based on ISO/TR 13387-2:1996.

(d) ISO/TR 13387-2:1996 was revised becoming ISO/TS 16733[5] in 2006 and has subsequently been broken into two parts. ISO 16733-1 Part 1 Selection of design fire scenarios[6] was published in 2015 and ISO 16733-2 Part 2 Design fires is under development at the time of writing.

(e) Hurley and Rosenbaum, Performance-based fire safety design - Chapter 4 Design fires. 2015, [7]

(f) Dowling and Ramsay, Building Fire Scenarios - An Analysis of Fire Incident Statistics. – Fire Code Reform Centre [8].

Design fires are generally characterised by one or more of the following parameters depending upon the specific circumstances:

- *Heat release rate* (HRR) versus time
- Peak HRR;
- Smoke and toxic production rates versus time
- Temperature or heat flux versus time
- Fire duration
- Fire position.

Alert

To provide a quantifiable benchmark to determine compliance with the *Performance Requirements* and ensure that the introduction of the *FSVM* would be policy neutral the *FSVM* adopted a compliance pathway based on comparison to the *Deemed-to-Satisfy Provisions*.

A significant advantage of a comparative approach is that the outcomes are less susceptible to assumed inputs and methods of analysis compared to absolute methods.

This can be demonstrated using an ASET / RSET analysis approach.

If an absolute compliance pathway approach is adopted and ASET is greater than RSET with an appropriate safety margin for an assumed "worst credible" *fire growth* rate the outcome could be assumed to be acceptable. However, if a faster growth rate had been selected as a "worst credible" *fire growth* rate ASET may have been less than RSET or the safety margin too small. Under these circumstances the outcome is dependent upon the selected *fire growth* rate and assumed occupant response / evacuation times and outcomes would be dependent upon the judgement of the PBDB team and in particular the fire safety engineers and *appropriate authority*.

If a comparative approach is adopted the outcomes are less sensitive to the selected growth rate particularly if the *fire growth* rates are unlikely to vary between the *reference building* and *Performance Solution.* Under these circumstances the selection of the *fire growth* rate will only be critical if the ranking of the consequences between the *reference building* and the proposed *Performance Solution* varies with the selected growth rate. This can be readily checked by undertaking a sensitivity study if there is any doubt.

1.1.2 Stages of Enclosure Design Fires

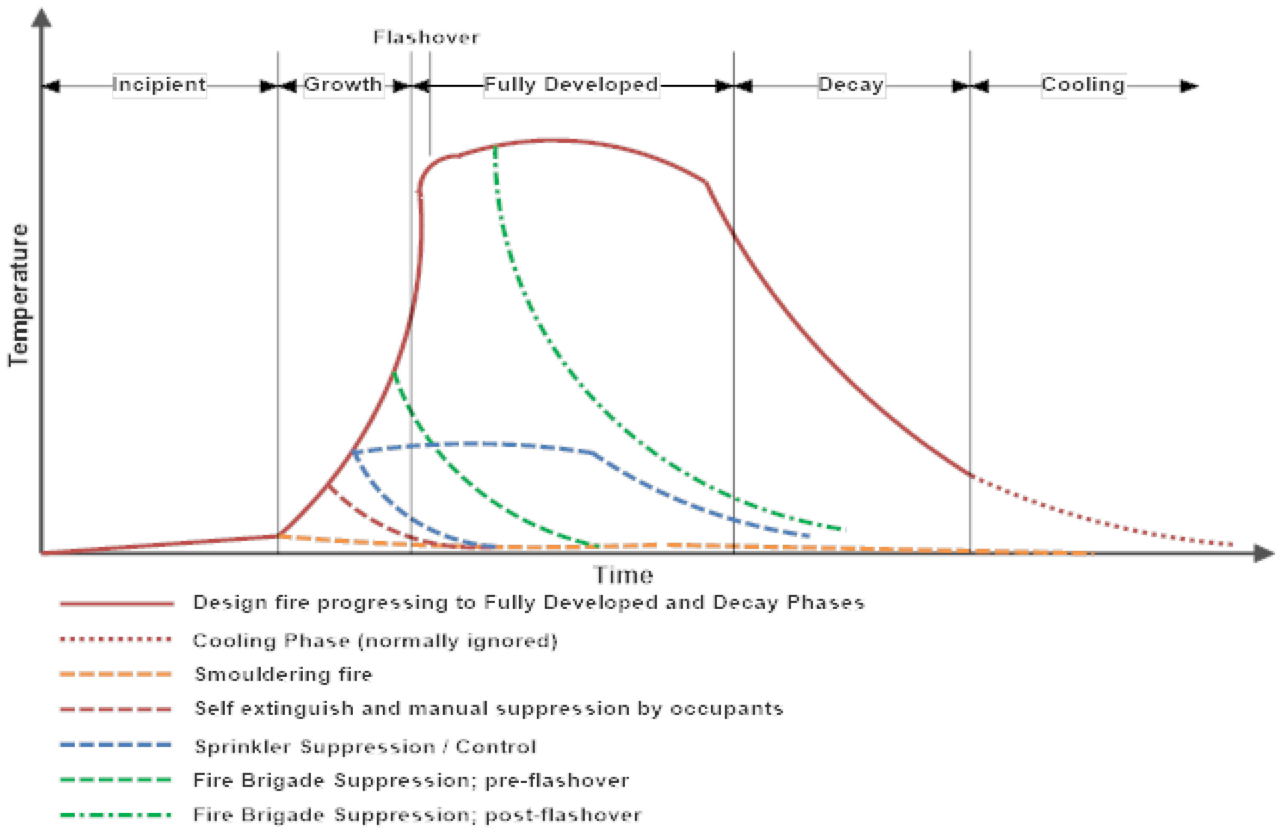
It is common to subdivide a *design fire* into the following four stages with a typical example shown in Figure 1:

- Incipient
- Growth
- Fully developed
- Decay.

A cooling phase has also been included in Figure 1 to identify scenarios where it is necessary to consider outcomes after extinction of the contents of the fire enclosure when there is no more energy being released from the enclosure contents. Typically, this may be necessary where degradation of elements of construction occurs after extinction of the contents due to thermal inertia, degradation on cooling (e.g. Dimia et al [9]) and / or combustion of elements of construction (e.g. McGregor [10]).

The incipient phase is commonly used for evaluation of smouldering fire (SF) scenarios in sleeping areas and in some scenarios the fire may not progress beyond the incipient phase. In other scenarios it is common to ignore the incipient phase unless detection during the incipient spread of fire is relevant to the comparative analysis being undertaken.

Figure 1 Design Fire Stages and Interventions



Also shown are typical interventions by occupants, *fire brigade* and *automatic* suppression / control systems (e.g. sprinklers) that modify the *design fire*.

Departures from this "traditional" representation of enclosure fires can occur in larger enclosures where a fully developed fire is unlikely to occur, and the fire remains localised, or the assumption of uniform combustion within the enclosure during the fully developed fire phase is no longer valid (refer section 1.4.4).

1.2 Incipient (Smouldering) Stage

The incipient phase is commonly described as a smouldering fire and generally applies to the smouldering fire (SF) scenarios. In other scenarios it is common to ignore the incipient phase unless detection during the incipient spread of fire is relevant to the comparative analysis being undertaken.

A smouldering / incipient fire tends to have a very low HRR, but the fire can readily change to a growing flaming fire, particularly when ventilation conditions change. Notwithstanding the low HRR, over a sufficiently long period, untenable conditions can develop presenting a hazard to occupants that may be asleep or otherwise incapacitated.

There are few models for the incipient phase, however the International Fire Engineering Guidelines[2] indicated that the following model adopted by Quintiere et al[11] for analysis of smouldering fire experiments is sometimes used to describe the pyrolysis rate for a smouldering fire in terms of mass loss;

$$\frac{dm}{dt} = 0.10t + 0.0185t^2 \text{ g/min}, 0 < t < 60 \text{ min}$$ Equation B1.1

$$\frac{dm}{dt} = 73 \text{ g/min}, 60 < t < 120 \text{ min}$$ Equation B1.2

where:

dm/dt is the pyrolysis rate in g/min and

t is the time in minutes.

It may be more appropriate to use experimental data particularly when determining activation times for smoke detectors and times to untenable conditions within the enclosure of fire origin. Typical examples of experimental data include Fire Code Reform Centre Smouldering & Flaming Fires - an Experimental Program, Moore and Beck [12] and the collated results analysed by Quintiere et al [11].

These studies tended to show that when untenable conditions occurred it was as a result of exposure to carbon monoxide within a closed enclosure of fire origin.

This is consistent with ISO 16733 2006[5] which notes that “the principal hazard associated with smouldering fires is the production of carbon monoxide as a result of incomplete combustion. The development of untenable conditions due to poor visibility is also a significant hazard that needs to be considered in the analysis, particularly in residential occupancies”.

Therefore, if tenability within the room of fire origin is being considered for a smouldering fire, additional tenability criteria relating to carbon monoxide should be introduced in addition to visibility and heat criteria generally applied in the *FSVM*.

1.3 Growth Stage

1.3.1 General

After the incipient stage, a fire may transition to a flaming fire corresponding to the *fire growth* stage. The characteristics of the *design fire* during this stage can be determined from one or more of the following sources:

- Full scale enclosure fire tests /experiments
- Furniture calorimeter tests
- Cone calorimeter tests
- Statistical data / fire incidents.

Growing fires are commonly characterised as a t-squared fire or a series of t-squared fires to address a range of credible *design fires* within an enclosure.

A t-squared fire is defined by the following equation;

$Q = \alpha t^2$ Equation B1.3

Where Q is the HRR – kW

t is the time – s

α is the proportionality constant (*fire growth* parameter) - kW/s^2.

A characteristic growth time (t_g – s), which is the time taken for the *design fire* to reach a reference HRR Q_g of 1055kW is also used to define t-squared fires in a way that can be more readily related to a fire scenario and can be converted to the proportionality constant using the following equation;

$\alpha = Q_g / {t_g}^2$ Equation 4

Whilst the proportionality constant can be derived for a specific application it is common to categorise a t-squared fire as indicated in Table 1 below.

Table 1 Typical t squared fire categories

Growth category	Proportionality constant α – kW /s^2	Growth time T_g - s
Slow	0.00293	600
Medium	0.0117	300
Fast	0.047	150
Ultra -fast	0.188	75

Compilations of fire test data relating to t-squared fires are available from various sources including NFPA 204[13] NFPA 72[14] and NFPA 92[15]. Derivations of t-squared fires based on analysis of fire statistics were undertaken by Holborn et al [16].

In some circumstances, it is reasonable to adopt general characteristic t-squared fires based on the building use. Under such circumstances, it is appropriate to consider a range of growth rates to check the design is not overly sensitive to the growth rate.

Data Sheet B2 provides characteristic t-squared fires for NCC building classes where appropriate together with details of the derivation. Characteristic values may be selected if more accurate information is unavailable, and the use of the characteristic values is agreed to during the PBDB process.

A proportion of fires will transition from the growth stage to fully developed fires (*flashover*) if there is no intervention with the remaining fires either peaking before *flashover* occurs or being constrained by limited ventilation (refer section 1.3.2).

1.3.2 Determination of Proportion of Localised Fires (Non-flashover Fires) and Potential Flashover Fires

The proportion of localised (non-*flashover*) fires can be determined based on data from fire incidents where the occupancy, and scenario(s) under consideration are broadly similar or can be calculated based on the estimated size of localised fires and undertaking modelling to determine if the fire will transition to a fully developed fire if there is no intervention.

Algebraic formulae for determining if *flashover* will occur are provided in the technical literature. The following documents are good examples:

- ISO 24678-6 2016 — Fire safety engineering — Requirements governing algebraic formulae — Part 6 Flashover related phenomena[17] presents details of many empirical correlations together with supporting data to determine their suitability for a particular application in Annex A.
- SFPE S.01 (2011) SFPE Engineering standard on calculating fire exposures to structures[18] provides a standardised approach based on the methods of McCaffrey, Quintiere and Harkleroad and Thomas but also identifies the following criteria for *flashover* if fire models are used:
  - Upper layer temperature exceeds 600°C or
  - Heat flux to the floor exceeds 20kW/m^2.

Characteristic values for the proportions of localised non-*flashover* fires estimated from fire incident data are provided in Data Sheet B2 which may be selected if more accurate information is not readily available, and the use of the characteristic values is agreed during the PBDB process.

The impact of interventions should also be considered to take account of the fire safety provisions within a building. This is discussed further in Section 1.5.

1.3.3 Enclosures with Localised Fires that do not Progress to Flashover

In some larger enclosures, particularly where the *fire load* is distributed in the form of discrete packages, the maximum HRR from a package may be insufficient to cause fire spread to other packages or to attain *flashover*. Typical examples include departure halls in travel terminals.

For these applications, the maximum fire sizes should be determined for the enclosure, based on identification of the maximum sizes of discrete fuel packages that will generate the largest fires and / or with the greatest potential to spread to adjacent fuel packages. The enclosure conditions can be modelled, or empirical correlations used to check if *flashover* or spread to other packages could occur. It is also necessary to define the maximum HRR and fire duration generally based on the rate of consumption of the fuel and amount of fuel within the fuel package to fully characterise the *design fire* and evaluate the exposure of occupants and building elements to the fire and products of combustion.

1.3.4 Flashover

For small and many medium sized enclosures, if a localised fire is large enough, *flashover* will occur. This may be described as a rapid transition occuring to a fire that simultaneously involves all exposed *combustible* surfaces within the enclosure. This marks a discontinuity in the combustion processes as the fire progresses to the fully developed phase.

In larger enclosures, *flashover* may not occur under all circumstances, and the fire remains localised as described in Section 1.3.3 or transitions to a travelling fire that progressively spreads through the enclosure rather than simultaneously involving all *combustible* surfaces within the enclosure.

1.4 Fully Developed Fires

1.4.1 General

During this stage the rate of HRR will tend to reach a maximum which will either be limited by ventilation or fuel and will be the lesser of a ventilation-controlled or fuel-controlled fire.

With ventilation-controlled fires, the maximum HRR within the enclosure will occur when the pyrolysis rate and the air supply rate are such that the conditions are close to stoichiometric.

If the pyrolysis rate is higher than the air supply rate, unburnt volatiles will be ejected from the enclosure and in some cases the inward airflow will be reduced. Thus, a significant amount of heat is generated outside the enclosure and the HRR within the enclosure is reduced.

The burning regime in fully developed fires may vary as the fire progresses.

For example, immediately after *flashover* the pyrolysis rate can be very high as small items with large surface area to mass ratios and materials that are easily pyrolysed are consumed leading to a strongly ventilation-controlled burning regime typified by long flame extensions from openings. As the fire progresses, the pyrolysis rate will tend to reduce until a peak HRR or temperature is reached within the enclosure close to stoichiometric conditions and flame extensions from openings substantially reduce. At some stage the fire will become fuel controlled with limited flame extension from openings.

The fire progression described above can vary due to changing ventilation conditions (e.g. additional openings formed during the fire) or changes in exposure of *combustible* materials due to failure of coverings, development of protective char layers or delamination.

For further details, reference should be made to detailed texts such as Drysdale[19].

During the fully developed fire stage, conditions within the enclosure are untenable and for many fire engineering applications, during this stage the *design fire* is characterised predominantly for evaluation of the ability of elements of construction to prevent fire spread and / or maintain structural stability of all or part of a structure.

Therefore, rather than expressing fires in terms of HRR, they are commonly expressed in terms of fire severity which can take the form of:

- an equivalent fire resistance test time of exposure – refer to data sheet B3 for details of a method based on Eurocode1 Part1-2 Annex F [20]

- a natural / realistic fire (expressed in terms of a temperature / time curve or for some applications a heat flux time curve) – refer to data sheet B3 for details of parametric temperature /time curves based on Eurocode1 Part1-2 Annex A [20].

1.4.2 Equivalent Fire Resistance Test Time of Exposure

Equivalent fire resistance test time of exposure is used to relate the severity of an expected real fire to the standard test fire assuming all the *fire load* is consumed. This approach is often preferred since it allows designers to directly derive and specify FRLs facilitating a choice of proprietary systems for fire protection systems to the structure, service penetrations and doors.

Alert

Equivalent fire resistance test time of exposure methods are commonly stated to be designing to survive *burnout* without structural collapse. However it should be noted that, if for example, an 80-percentile *fire load* is assumed there will be a probability of 0.2 that the equivalent fire resistance time of exposure will be under predicted and hence structural collapse with the assumed *fire load* distribution may occur. In reality, the situation is more complex since other variables need to be considered requiring further assumptions, but for transparency it is more appropriate to refer to a design that restricts the probability of failure of the structure to an acceptable level.

1.4.3 Enclosure Time-temperature Relationships

Parametric time-temperature relationships have been derived for fully developed fires and the subsequent decay stages, assuming uniform burning and homogenous temperature conditions throughout the compartment and the *fire load* is consumed within the enclosure. A typical example is Eurocode1 Part1-2 Annex A [20].

The derived *design fire* expressed in terms of imposed temperature or heat flux as a function of time enables cross-sectional temperatures of elements of construction to be predicted. If appropriate material properties are known, the structural performance can also be determined and /or the scenario time to failure predicted which enables events such as failure of an element to be included in a time line analysis of a scenario.

The method is particularly suited to analysis of structural elements where material properties at elevated temperatures are well known. The structural analysis can be applied to individual elements, parts of a structure or the whole structure and analysis methods vary from simple lumped thermal mass calculations to detailed finite element analysis used in conjunction with appropriate material properties at elevated temperatures and the time to failure accordingly determined.

However, such calculations may not be able to be undertaken for some elements of construction such as fire doors and penetration seals due to the complexity of material and element behaviour. In such cases, the approach described in Section 5.2 or that described below will be appropriate and the equivalent fire exposure duration, so determined, can be compared with the performance obtained from *Standard Fire Tests* associated with the particular element.

An approximate estimate can be made by correlating the times to a critical temperature or other event relating to failure for a representative element exposed to both the standard fire heating regime and the *design fire* heating regime. Increased confidence in this approach can be obtained if the results can be compared to test data with similar elements of construction subjected to differing heating regimes such as the standard and hydrocarbon heating regimes.

1.4.4 Travelling Fires

The term “travelling fires” has been used to describe fire scenarios where a fire progressively spreads through a large enclosure rather than involving all *combustible* surfaces simultaneously.

Modelling methods for travelling fires based on the superposition of the impact of a series of localised fuel controlled fires in the vicinity of the element under consideration have been proposed and a literature review and design methodology have been described by Stern-Gottfried et al[21, 22] based on a number of simplifying assumptions including the assumption of a fuel controlled fire.

Thomas et al[23, 24] described experiments in deep enclosures with single ventilation openings where the fire was initially ventilation controlled and the fire spread towards the ventilation opening initially, and once the fuel close to the ventilation opening was consumed progressively spread to the back of the enclosure. This behaviour imposes significantly higher fire exposures on elements close to the ventilation opening compared to those at the rear of the enclosure.

Since models to simulate the above types of behaviour are limited as is data on which to validate the models, a pragmatic solution can be adopted by undertaking a sensitivity analysis for a range of fire durations. Since the *FSVM* adopts a comparative approach it is generally only critical to determine that the consequences for each scenario for the proposed *Performance Solution* are less severe than those for the *reference building* unless it is determined that there is potential significant hazard.

1.4.5 Decay and Cooling Stages

The decay and cooling stages are commonly treated as an extension of the fully developed stage with progressive reductions in exposure temperatures or heat flux from combustion of the exposed *combustible* contents or heat transfer from hot surfaces. During this stage, the structural capacity of sections may continue to reduce as a result of thermal inertia within a section or continued deterioration of structural elements and thermal stresses may modify loading conditions.

1.5 Interventions

1.5.1 General

The previous sections have discussed the progression of a *design fire* without interventions. An analysis performed using the FSVM includes a range of *design* *scenarios.* All fire protection systems are required to be fully operational for some *design scenarios* whilst others require consideration of failure of key systems.

Therefore, if a fire safety strategy includes *automatic* suppression the *design fire* is modified to take account of *automatic* fire suppression unless the *design scenario* under consideration requires consideration of failure of key *fire safety systems*.

The need to modify *design fires* to account for the impact of *fire brigade* intervention when using the FSVM is dependent on the nature and extent of the variations between the *reference building* and proposed *Performance Solution*, the *design scenarios* under consideration and selected methods of analysis.

Since the FSVM adopts a comparative approach in many instances, it will only be necessary to determine that the timing of *fire brigade* intervention, size of fire and conditions facing the fire fighters at the time of intervention will be the same (or earlier and less severe) for the proposed *Performance Solution* compared to the *reference building* and there is therefore no need to modify a *design fire* to account for *fire brigade* intervention.

However, there may be some instances where variations between the proposed *Performance Solution* and *reference building* are such that the impact of fire brigade intervention on the *design fire* should be accounted for, particularly with *design scenarios* that include failures of key fire protection systems and the timing of *fire brigade* intervention varies between building solutions being compared.

Under these circumstances, the approach to be taken should be agreed as part of the PBDB. Input from the relevant *fire brigade* is critical since the operational procedures and capabilities will need to be considered.

Ventilation conditions can significantly impact the *design fire* at all stages and therefore potential changes must be considered for all scenarios.

1.5.2 Automatic Suppression

The most common *automatic* suppression systems are *automatic* fire sprinkler systems (sprinkler systems) which are discussed further in this section but many of the principles discussed below can be applied to other *automatic* suppression systems.

Sprinkler systems can be designed with the objective of either controlling or suppressing a fire.

The configuration of the contents of a building can be such that burning objects may be shielded from the sprinkler discharge and therefore it is usual, even with sprinkler systems designed to suppress fires, to assume that a proportion of fires will be controlled rather than suppressed.

Common design approaches include;

- reference to experimental studies and / or
- estimation of the activation time for sprinkler heads and then assume either a constant HRR (equal to the *design fire* HRR at the time of activation) or a correlation for the reduction in HRR. Further guidance is provided in the technical literature including the International Fire Engineering Guidelines[2].

1.5.3 Intervention by Fire Brigade

If the impact of *fire brigade* intervention is to be considered typically the following will need to be determined as a minimum:

- Available fire-fighting resources and demand on resources
- Conditions fire fighters are exposed to
- The time to application of water (generally based on use of the AFAC FBIM[25] notification time, and building proximity to fire stations)
- The fire size at the time of application of water
- The number of hose lines and water supply available for fire-fighting purposes
- The extent of containment of the fire.

In consultation with the relevant *fire brigade* the probability of suppression, control or protection of exposures can then be determined. Control or suppression of a fire will only be achieved if it is within the capabilities of the appliances and fire fighters in attendance and fire-fighting equipment and water supplies available.

1.5.4 Ventilation Conditions

1.5.4.1 Summary of Features Influencing Ventilation Conditions

Ventilation conditions can have a significant impact on *design fires* and the following matters should be considered to the degree necessary for the scenarios being considered:

- Air flows due to HVAC systems and natural ventilation
- Impact of smoke control systems if activated
- Changes to enclosure openings and boundaries.

1.5.4.2 HVAC Systems and Natural Ventilation

Without an adequate air supply, a fire will self-extinguish due to a lack of oxygen. In a small enclosure the *fire growth* rate may therefore be modified unless air is supplied through openings (e.g. an open door or window) or an operational HVAC system.

For design purposes, it is generally conservative to assume that the air supply does not constrain the growth of a fire and the potential progression to *flashover*.

Air flows associated with active and passive ventilation systems can impact plume development and direct the flow of products towards or away from occupants and smoke / heat detection devices including sprinkler heads. Therefore, when deriving *design fires* these matters should be considered if the comparison between the proposed *Performance Solution* and *reference building* is expected to be materially affected.

Design standards for *automatic* suppression and fire detection systems commonly provide guidance on matters such as placement of detectors to address the above issues and therefore special attention should be provided when a proposed *Performance Solution* incorporates variations from design standards for suppression and detection systems.

1.5.4.3 Smoke Control Systems

Once activated, smoke control systems will modify the ventilation / airflow conditions within a building in a similar manner to the HVAC systems and natural ventilation systems except that in some instances airflows may be greater, increasing the impact on *design fires.*

Typical examples include:

- High velocity make-up air inlets close to a fire position which can:
    - substantially increase the HRR accelerating the growth rate and potentially maximum fire size and /or
    - deflect the plume potentially causing higher smoke concentrations in occupied areas.
- A smoke vent or exhaust system may remove hot gases from an enclosure prior to activation of a sprinkler system, potentially compromising the performance of the sprinkler system especially systems designed for early suppression.

Design standards for *automatic* suppression and fire detection systems commonly include provisions to address these issues and therefore special attention should be provided when a proposed *Performance Solution* incorporates variations from design standards for suppression and detection systems.

1.5.4.4 Changes to Enclosure Openings and Boundaries

Openable doors and windows can substantially change ventilation conditions during a fire scenario influencing *fire growth* and ventilation conditions during the fully developed stage, which can have a significant impact on the *design fire* severity as well as the spread of products of combustion throughout the building.

The status of door and window openings used to derive *design fires* should be clearly stated and taken account of.

The boundaries of an enclosure are often a mix of *fire-resisting* construction with unprotected openings (openings typically sealed by elements that do not have a minimum FRL prescribed that may or may not be openable) and internal walls that may not be required to be *fire-resisting* (e.g. non-loadbearing walls located wholly within an apartment).

At some stage during a fire scenario that progresses to a fully developed fire, these elements may totally or partially fail modifying the ventilation conditions and allowing spread to adjacent enclosures. The timing and extent of these failures varies with the form of construction and in particular the elements' inherent fire-resistance.

For example, a closed window may fail totally or partially during the growth phase whereas an internal non-loadbearing wall may be capable of achieving an inherent FRL in the range of -/20/20 to -/60/60 depending on the wall construction.

The consequence of this is that the fire enclosure dimensions, fuel and ventilation conditions may change during a scenario modifying the *design fire* substantially, particularly during the fully developed stage.

The variability of these parameters can be addressed by considering a range of values during a sensitivity analysis and checking the ranking of the proposed *Performance Solution* and *reference building* does not change.

1.6 References

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Data Sheet B2: Design Fires – Characteristic Input Data

Group B Data Sheets provide typical input data and guidance relating to the derivation of *design fires* and supplements guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

Use of information from Group B Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet (B2) provides supporting data for the derivation of *design fires* and should be read in conjunction with the FSVM Handbook and other Group B Data Sheets which include:

- Data Sheet B1: Design fires - overview
- Data Sheet B3: Design fires – typical calculation methods for fully developed fires
- Data Sheet B4: Design fires – simple design fires for comparison of wall and ceiling linings.

Design fires for Horizontal Fire Spread between Buildings (HS) and Vertical Fire Spread (VS) scenarios are not addressed since these scenarios are predominantly addressed in *Verification Methods* CV1 to CV3.

This Data Sheet focusses on the content relating to the FSVM and in particular areas where a level of standardisation with respect to the selection of input data and / or analysis methods is considered useful. It does not cover all relevant inputs and should not be used without giving full consideration and applying sound engineering judgement to the selection of fire safety strategies, inputs and methods of analysis.

For example, carbon monoxide yields are not specified because carbon monoxide exposure is not prescribed as a general tenability criterion in the FSVM.

Data Sheet B2 Contents

Version	Date	Data	Comments
B2-1	Dec 2018	B2	Final draft for comment
B2-2	Jun 2019	B2	Draft for publication

1.1 Characteristic Growth Rates and Parameters for t-squared Fires

1.1.1 Growth Categories and Selected Clusters

A t-squared fire is defined by the following equation:

$Q = \alpha t^2$ Equation B2.1

Where Q is the HRR – kW, t is the time – s and α is the proportionality constant (*fire growth* parameter) - kW/s^2.

A characteristic growth time (t_g – s), which is the time taken for the *design fire* to reach a reference HRR Q_g of 1055kW is also used to define t-squared fires in a way that can be more readily related to a fire scenario and can be converted to the proportionality constant using the following equation:

$\alpha = Q_g/{t_g}^2$ Equation B2.2

Whilst the proportionality constant can be derived for a specific application it is common to categorise a t-squared fire as slow, medium, fast and ultra-fast as indicated in Table 1. The very slow growth category and clusters of growth times assigned to each growth category used by Holborn et al[2] for analysis of *fire growth* rates using data from fire investigations have been included in Table 1.

Table 1 Typical t-squared fire categories

Growth category	Proportionality constant α (kW /s^2)	Growth time T_g (s)	Growth time range cluster (s)
Very slow	0.000412	1600	>1600
Slow	0.00293	600	400-1600
Medium	0.0117	300	200-400
Fast	0.047	150	100-200
Ultra -fast	0.188	75	<100

1.1.2 Characteristic Values

Table 2 provides *fire growth* rate distributions (expressed as a percentage of fires) for various occupancies based on analysis of fire incident data undertaken by Holborn et al [2] in which log normal distributions were derived for growth rates. The samples were small for some building classes and therefore the number of incidents available for analysis (N) is quoted in the table for consideration by users of the data. The shaded boxes indicate t growth rates published in the Practice Note for *design fires* prepared by Engineers Australia SFS[3] which is based on values listed in various national and regional standards.

Table 2 Characteristic Fire Growth Rate Distributions for Various Occupancies

NCC Typical Building Class	Building Occupancy Description	t-squared fire growth rate / percentage of fires: very slow	t-squared fire growth rate / percentage of fires: slow	t-squared fire growth rate / percentage of fires: medium	t-squared fire growth rate / percentage of fires: fast	t-squared fire growth rate / percentage of fires: ultra-fast	N
Class 2,	Residential	34	50	11	>4.5	<0.5	481
Class 3	Hotel (room)	48	42	7	3	N/A	12
Class 3 / 9c	Care	46	53	1	N/A	N/A	9
Class 4	Residential	34	50	11	>4.5	<0.5	-
Class 5	Office	35	53	9	3	N/A	19
Class 6	Retail	10	47	25	13	5	37
Class 6	Licensed premises	29	47	15	6	3	17
Class 7a	Carpark	N/A	N/A	N/A	N/A	N/A	N/A
Class 7b	Display area	N/A	N/A	N/A	N/A	N/A	N/A
Class 7b	Storage and warehousing	21	8	29	24	18	6

Class 8	Teaching laboratories	N/A	N/A	N/A	N/A	N/A	N/A
Class 8	Workshop	N/A	N/A	N/A	N/A	N/A	N/A
Class 8	Factory	19	46	20	10	5	16
Class 9a	Hospital (room)	29	65	>5.5	<0.5	N/A	17
Class 9b	Library	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b	Picture gallery	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b	Classroom of a school	40	47	9	4	N/A	16
Class 9b	Gymnasium	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b	Assembly hall seating	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b	Public building	20	53	18	7	2	10
General	All excluding dwellings	26	51	15	6	2	164
Various	Kitchen	N/A	N/A	N/A	N/A	N/A	N/A

For building classes and occupancies which are common to the Engineers Australia SFS Practice Note, it is noted that the growth rate nominated by the SFS Practice Note is equal to or greater than that nominated by the Holborn study for at least 95% of the fires reported.

If more relevant information is unavailable, the characteristic t-squared fires from Table 2 can be selected based on the building class or use of an area provided the use of the characteristic values has been accepted by the relevant stakeholders during the PBDB process. If the results are expected to be sensitive to the growth time, the outcomes for the proposed *Performance Solution* should be compared to the *reference building* for a range of the commonly occurring growth times identified in Table 2.

1.2 Characteristic Proportion of Fully Developed Fires Assuming No Automatic Suppression

1.2.1 Characteristic Values

Characteristic values for the proportions of localised non-*flashover* fires estimated from fire incident data are provided in Table 3 which may be selected if more accurate data is not available, and the use of the characteristic values has been accepted by the relevant stakeholders during the PBDB process.

Table 3 Characteristic Proportion of Potential Fully Developed Fires by NCC Building Class

Fire Type	Class 2,4	Class 3 9a and 9c	Class 5,6,7 8 and 9b
Non-*flashover*	82	95	85
Flashover fires	18	5	15

The estimates of the proportion of localised (non-*flashover*) fires and potential *flashover* fires assumes no intervention by *automatic* suppression systems. The estimates were based on the extent of fire spread and / or extent of damage obtained from published fire data as described below with rounding of the values to reflect the assumptions and approximations required for the derivation. Generally conservative assumptions have been made when deriving the estimates.

For large enclosures with discrete *fire loads* it is possible that *flashover* may not occur. Typical examples could be large halls in transport terminals.

1.2.2 Derivation of Characteristic Values

The proportion of potential *flashover* fires for Class 2 buildings (apartments) derived from the extent of fire spread was reported in Apte et al[4] based on the work of Yung and Benichou and Narrayanan and Whiting. The resulting estimates are summarized in Table 4 with unknown fires sizes in the NZ data proportionally distributed.

Table 4 Proportions of Flashover Fires in Dwellings

Fire Type	Australia	USA	Canada	NZ
Smouldering fire	24.5%	18.7%	19.1%	27.0%
Non-*flashover* fire	60.0%	63.0%	62.6%	49.8%
Flashover fire	15.5%	18.3%	18.3%	23.2%

Since most households are single dwellings, it is reasonable to assume that very few of these fires occurred in sprinkler protected buildings and therefore it is estimated that approximately 18% of fires would progress to *flashover* if no *automatic* fire sprinklers are present.

Holborn et al [2] undertook an analysis of fire sizes, *fire growth* rates and times between events using data from fire investigations in the Greater London area between 1996 and 2000. As part of this analysis, log normal distributions were derived for the fire damaged areas for a range of occupancies.

This enabled the percentage of fires above a specified size to be calculated. The size of fire for *flashover* to occur varies with the size of enclosure amongst other things. For small enclosure sizes such as those in residential buildings, a value of 10m^2 of fire damage was assumed to estimate the proportion of *fully developed fire* yielding a probability of *fully developed fires* occurring of 17% which is comparable with the 18% determined by Apte. For large areas (factories and warehouses) a damage area of 100m^2 was adopted and for mixed enclosure sizes 20m^2 was adopted. The correlations and calculations are presented inTable 5.

Table 5 Extent of Fire Damage and Estimate of Proportion of Fully Developed Fires: A) Log Normal Distribution Parameters and B) % of Fire with Damage Greater Than

Occupancy	Num of fires	A) Mean	A) SD	A) E(x)	B) 10m^2	B) 20m^2	B) 100m^2	Encl. Size Class	Est. Prob. of FO %
Residential	1191	0.9	1.45	7	16.7	7.4	N/A	S	17

Occupancy	Num of fires	A) Mean	A) SD	A) E(x)	B) 10m²	B) 20m²	B) 100m²	Encl. Size Class	Est. Prob. of FO %
Care homes	17	-0.64	1.44	1	2.1	0.4	N/A	S	2
Hospitals	30	-0.08	1.28	2	3.1	0.8	N/A	M	1
Hotels	38	-0.29	1.52	2	4.4	1.5	N/A	S	4
Licenced premises	50	0.78	1.7	9	18.5	9.6	N/A	M	10
Schools	34	0.69	1.89	12	19.7	11.1	N/A	M	11
Retail	94	1.17	1.84	18	26.9	16.1	N/A	M	16
Further education	14	0.56	2.24	22	21.8	13.8	N/A	M	14
Offices	63	0.83	2.14	23	24.6	15.6	N/A	M	16
Factories	47	1.68	1.91	33	37.2	24.5	6.3	M / L	6-25
Public buildings	34	1.8	1.92	38	39.7	26.7	7.2	M / L	7-27
Warehouses	20	2.87	2.13	170	60.5	47.6	20.8	L	21
All (excl. residential)	441	0.92	1.99	18	24.4	14.8	N/A	M	15

Care homes, hospitals and hotels have particularly low proportions of fires progressing to *flashover* based on the above analysis. Typically, these premises are likely to have 24-hour staff and monitored smoke detection systems present which would alert the *fire brigade* to a higher proportion of fires than normal residential buildings and other occupancies where a high proportion of small fires would be unreported. This also explains to some extent the very high frequency of reported fires in hospitals. In Table 3, a characteristic value of 5% was assigned for potential *fully developed fires*.

Most other building estimates lie in the range of 10-20% of reported fires progressing to *flashover* and since the selected damage areas and typical enclosure size estimates involved subjective judgements and the sample sizes were relatively small, a characteristic value of 15 % was assigned for the proportion of *fully developed fires*. An exception was made for dwellings (including Class 2 apartments) where the sample size was substantially larger and the estimated value of 18 % was retained.

1.3 Fire Loads

1.3.1 Characteristic Values

Project Report FCRC-PR 01-02[5] reviewed *fire load* survey results in 1999 and provided estimates based on the mean of the surveys and then weighted estimates based on a ranking of the available sources by a panel of experts. The characteristic values estimated from that study have been updated to reflect more recent studies and *fire loads* assigned to four categories as shown in Table 6. Normal distributions were adopted except for the very high case where fixed minimum and maximum limits were applied to avoid extreme values resulting from the large standard deviation. (Note: by applying limits the normal distribution may be skewed).

Table 6 Characteristic Fire Load Distributions for NCC Buildings

Building Class	Fire Load Category	Mean Fire Load MJ/m^2	Standard Deviation MJ/m^2	Min MJ/m^2	Max MJ/m^2
Class 6, 7b, 8, 9b	Very High	1000	750	300	2500
Class 5, 9b	High	780	115	200	unlimited
Class 2,3,4,9b, 9c	Medium	500	150	200	unlimited
Class 7a (excl. stackers) Class 9a (*ward areas*)	Low	300	90	100	unlimited

The *fire loads* in Table 6 ignore any contribution from wall and ceiling linings and the structure and adjustments should be made for *combustible* linings / exposed structural elements. Two values have been quoted for *assembly buildings*. In most assembly occupancies, the *fire load* would be expected to fall into the medium category or less but for public buildings such as libraries the *fire load* could be high.

The distributions for the *fire load* categories are shown in Figure 1 through Figure 4.

The *fire load* category applied to Class 7b occupancies excludes high-rack storage. The very high *fire load* distribution with a mean of 1000 MJ/m^2, standard deviation of 750 MJ/m^2 and truncated at maximum and minimum values of 2500 and 300 MJ/m^2 respectively was adopted which reflects the high variability of *fire loads* within Class 6, 7b and 8 buildings.

The characteristic *fire load* distributions may be adopted subject to acceptance by the relevant stakeholders during the PBDB process if more accurate data is not available. Depending on the selected method of analysis the full distribution can be selected, or a percentile value adopted for design purposes subject to agreement of the relevant stakeholders during the PBDB process.

Figure 1 Characteristic Fire Load Distribution for Very High Category

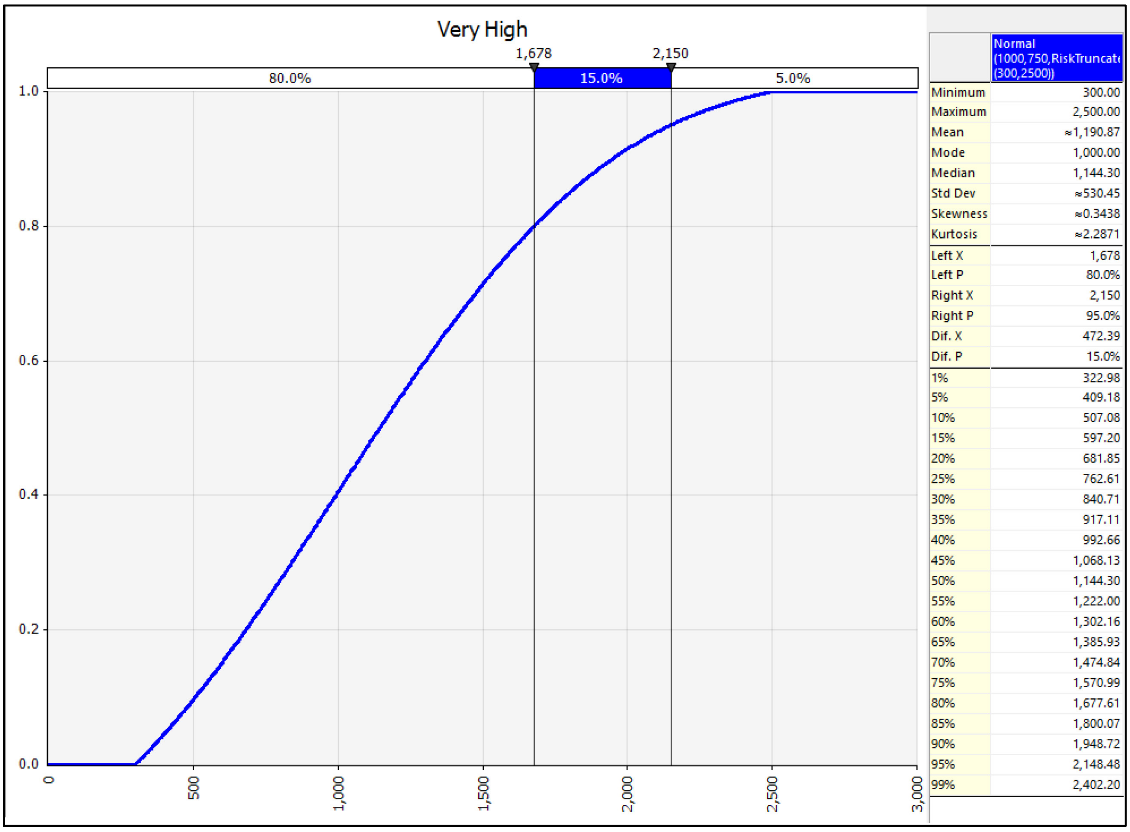


Figure 2 Characteristic Fire Load Distribution for High Category

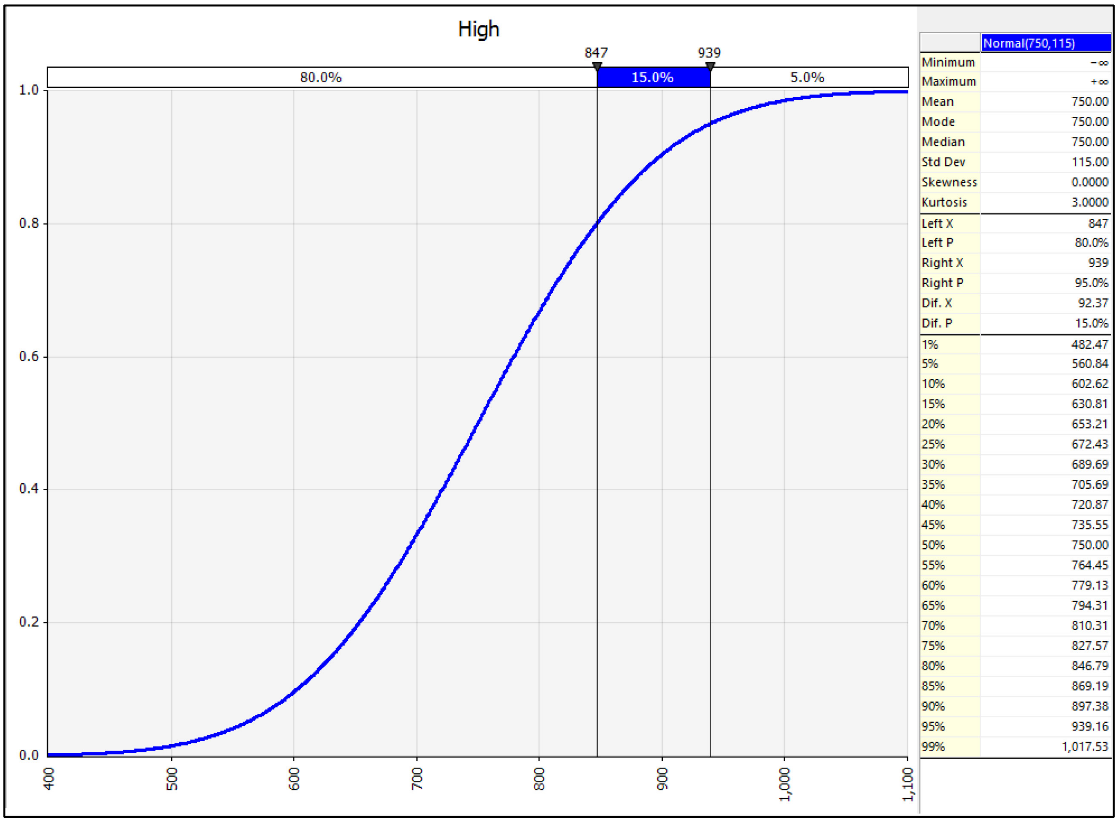


Figure 3 Characteristic Fire Load Distribution for Medium Category

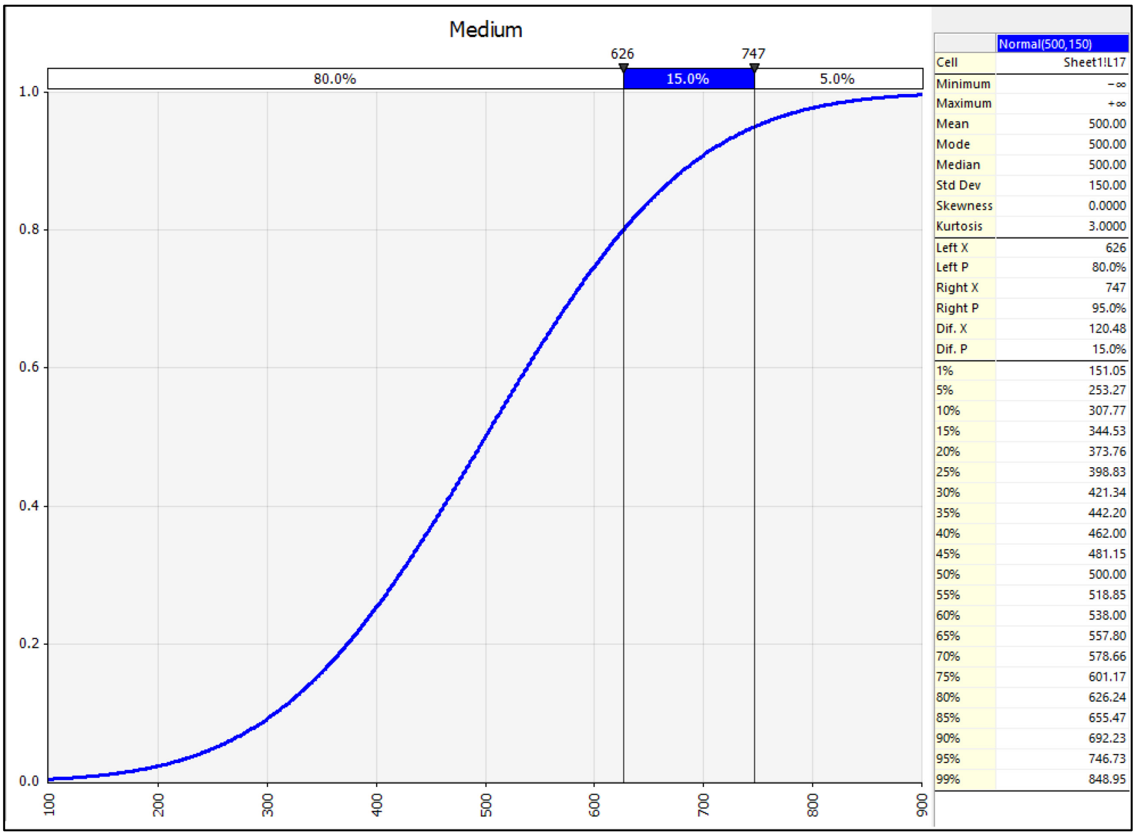
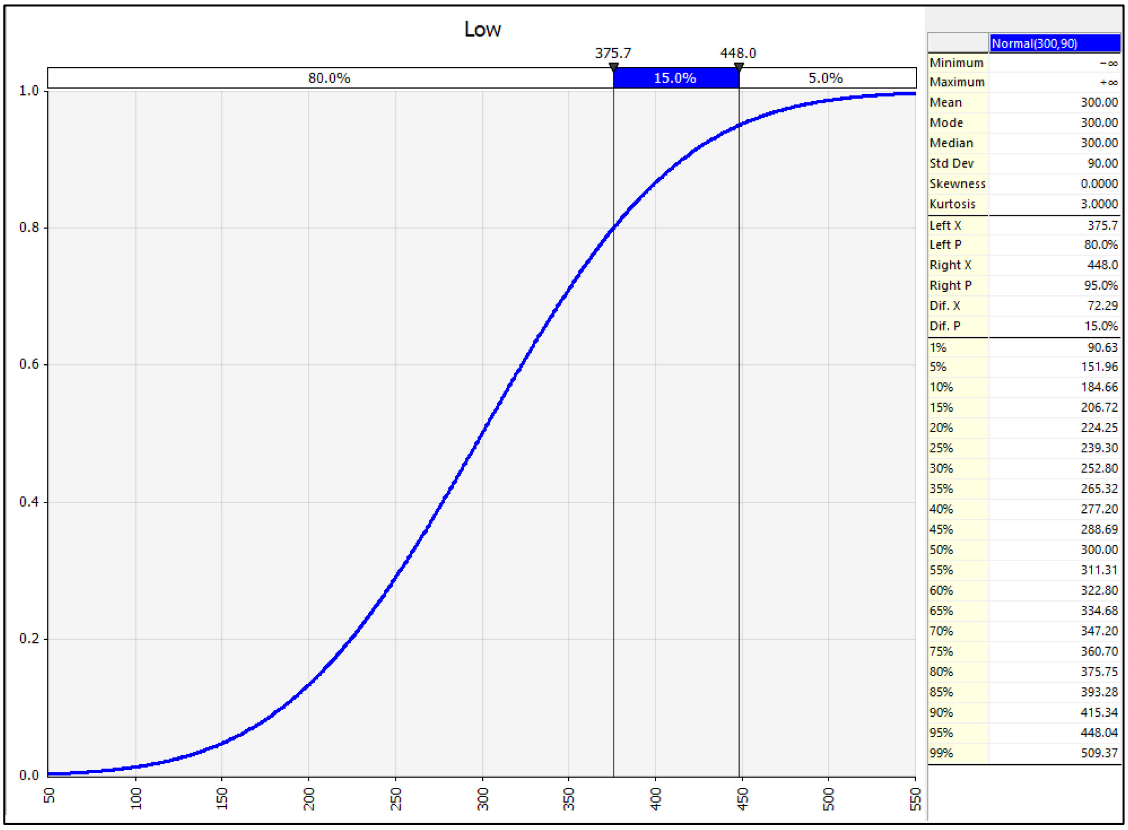


Figure 4 Characteristic Fire Load Distribution for Low Category



1.3.2 Derivation of Characteristic Fire Loads

Details of the supporting data used to inform the selection of *design fires* has been summarised below to enable users to determine the suitability of the characteristic values for a particular application and to select appropriate design values.

Project Report FCRC-PR 01-02[5] reviewed *fire load* survey results for total *fire load* (fixed and variable) in 1999 and provided estimates based on the mean of the surveys and weighted estimates based on a ranking of the available sources by a panel of experts. The estimates from this study have been updated to reflect other studies as listed in Table 7. In the characteristic values provided in Table 6, the *fire load* contribution from the structure and linings is excluded and therefore the total *fire load* from the FCRC study may provide an overestimate of the *fire load* excluding fixed *fire loads*.

The *fire loads* for each class or sub-class of building were then allocated to one of four *fire load* categories (low, medium, high and very high) and for each category a mean value, standard deviation and where appropriate minimum and maximum values were selected.

Eurocode 1 Parts 1-2[6] recommends 80-percentile for characteristic variable *fire load* density assuming a Gumbel Distribution. If an 80-percentile value is adopted the *fire safety engineering* design for the building will need to address the 20% of cases where the *fire load* is exceeded. Characteristic values are then modified by the Eurocode to account for the rate of fire starts and active measures and a combustion factor introduced to account for combustion efficiency. Adjustments for fire starts and active measures should not be used to demonstrate compliance with the NCC because the impact of these measures should be derived as part of a fire engineering analysis having regard for the specific building solutions under consideration.

New Zealand C/VM2 Verification Method: Framework for Fire Safety Design[7] includes characteristic values for the *fire load* energy density based on activities performed in a space. These were assigned to the most relevant class.

FCRC Survey - Bennetts et al [8]; includes surveys of specialty shops and reported a range of values from 738-3240 MJ/m^2 assuming heat of combustion for timber of 18 MJ/kg.

Ocran Fire Loads and Design fires for Mid-Rise Buildings[9]; provides a more recent review of available surveys for residential and office occupancies.

Khorasani et al 2014[10]; undertook a review of office fire loads from historic and more recent surveys of offices. Areas with high fire loads (heavy) such as storage areas and low fire loads (light) such as meeting rooms are considered separately. The review also identified different correlations for large and small enclosures.

Zalok et al[11] reported a Canadian survey of 168 retail outlets ranging from 3.25m^2 to 1707m^2 The minimum, mean and maximum fire loads were 56, 747 and 5305MJ/m^2 respectively and a log normal distribution was fitted with a standard deviation of 833MJ/m^2.

Table 7 Summary of Fire Loads and Design Values

Building Class /Sub Class	Eurocode 1 Parts 1 and 2: Mean	Eurocode 1 Parts 1 and 2: 80%	Eurocode 1 Parts 1 and 2: 0.8 Comb	FCRC - Fixed and variable: Mean	FCRC - Fixed and variable: SD	NZ C/VM2: Char.	Ocran: Mean range	Khorasani et al mean: Light	Khorasani et al mean: Heavy	Zalok et al: Mean	Zalok et al: SD	FCRC Survey: Range	Fire Load Category	Adopted Values: Mean	Adopted Values: SD	Adopted Values: Min
Class 2 dwelling	780	948	758	1000	300	400	370-550	N/A	N/A	N/A	N/A	N/A	Med	500	150	200
Class 3	310	377	302	500	150	400	370-552	N/A	N/A	N/A	N/A	N/A	Med	500	150	200
Class 4	780	948	758	1000	300	400	370-557	N/A	N/A	N/A	N/A	N/A	Med	500	150	200
Class 5 office	420	511	409	800	480	800	348-1321	733-295	1847-384	N/A	N/A	N/A	High	780	115	200
Class 6 shop	600	730	584	1000	500	800	N/A	N/A	N/A	747	833	738-3240	Very High	1000	750	500
Class 7a carpark	N/A	N/A	N/A	200	60	400	N/A	N/A	N/A	N/A	N/A	N/A	Low	300	90	100

Building Class /Sub Class	Eurocode 1 Parts 1 and 2: Mean	Eurocode 1 Parts 1 and 2: 80%	Eurocode 1 Parts 1 and 2: 0.8 Comb	FCRC - Fixed and variable: Mean	FCRC - Fixed and variable: SD	NZ C/VM2: Char.	Ocran: Mean range	Khorasani et al mean: Light	Khorasani et al mean: Heavy	Zalok et al: Mean	Zalok et al: SD	FCRC Survey: Range	Fire Load Category	Adopted Values: Mean	Adopted Values: SD	Adopted Values: Min
Class 7b storage / wholesale	N/A	N/A	N/A	5500	3900	1200	N/A	N/A	N/A	N/A	N/A	N/A	Very High	1000	750	500
Class 8 laboratory / factory	N/A	N/A	N/A	600	420	1200	N/A	N/A	N/A	N/A	N/A	N/A	Very High	1000	750	500
Class 9a hospital	230	280	224	350	110	400	N/A	N/A	N/A	N/A	N/A	N/A	Low	300	90	100
Class 9b assembly: cinema	300	365	292	N/A	N/A	800	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b assembly: library	1500	1824	1459	750	230	800	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b assembly: transport	100	122	98	N/A	N/A	400	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Class 9b assembly: typical	N/A	N/A	N/A	N/A	N/A	400	N/A	N/A	N/A	N/A	N/A	N/A	Med	500	150	200

Building Class /Sub Class	Eurocode 1 Parts 1 and 2: Mean	Eurocode 1 Parts 1 and 2: 80%	Eurocode 1 Parts 1 and 2: 0.8 Comb	FCRC - Fixed and variable: Mean	FCRC - Fixed and variable: SD	NZ C/VM2: Char.	Ocran: Mean range	Khorasani et al mean: Light	Khorasani et al mean: Heavy	Zalok et al: Mean	Zalok et al: SD	FCRC Survey: Range	Fire Load Category	Adopted Values: Mean	Adopted Values: SD	Adopted Values: Min
Class 9b assembly: high	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	High	780	115	200
Class 9b school	285	347	278	500	150	400	N/A	N/A	N/A	N/A	N/A	N/A	Med	500	150	200
Class 9c aged accommodation	N/A	N/A	N/A	N/A	N/A	400	370-550	N/A	N/A	N/A	N/A	N/A	Med	500	150	200

1.4 Smoke (Soot) Yields and Heats of Combustion

1.4.1 Overview

Depending on the method of analysis adopted, it may be necessary to define the mass of particulates produced by the *design fire* (commonly referred to as smoke or soot yields) to determine smoke detector activation times and visibility.

Typically, the rate of production of particulates is expressed as the smoke or soot yield Y_s which is the ratio of the mass of particulates produced to the mass of material burnt.

If a *design fire* is expressed as a HRR it is necessary to convert the HRR to a mass burning rate using the relationship:

$$\dot{Q} = \Delta H_{ch} \dot{m}$$ Equation B2.3

The chemical heat of combustion (effective heat of combustion) ΔH_{ch} allows for combustion efficiency and is the product of combustion efficiency and the net heat of complete combustion per unit mass of fuel consumed (Δ_T).

1.4.2 Characteristic Smoke / Soot Yields for Well Ventilated Design Fires

The soot yields for common materials are shown in Table 8 together with the chemical heats of combustion for well ventilated fires based on bench scale tests performed using the ASTM E2058 fire propagation apparatus exposed to constant heat flux supplemented by other cone calorimeter data. The data was obtained from results published by Tewarson [12] and Klote and Milke [13].

However, studies successfully correlating data obtained from small-scale tests to a larger scale are limited and therefore extrapolation of small-scale data for use in modelling building fires should be undertaken with caution.

Since the FSVM adopts a comparative approach, the sensitivity of the analysis to the selected soot yields will tend to be less than an absolute study because for most applications the same yield will be adopted for the proposed *Performance Solution* and the *reference building*. Notwithstanding this, a sensitivity study can be undertaken if there is a concern that the ranking of the building solutions may change if an alternative soot yield is adopted.

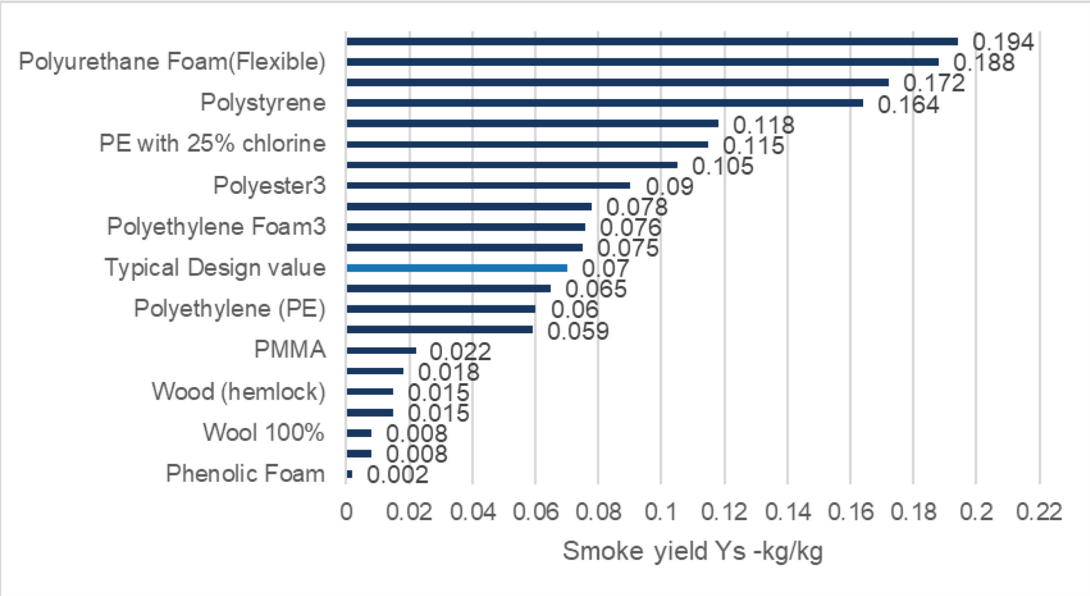
A characteristic value for the soot yield of 0.07kg/kg and a heat of combustion of 20 MJ/kg is specified in New Zealand Verification Method CV2 [14] for pre-*flashover* (well ventilated) *design fires* and may be an appropriate indicative value if the constitution of a *fire load* is unknown. Figure 5 presents a bar chart of the soot yields in ascending order with the characteristic value of 0.07kg/kg inserted for comparison.

Table 8 Soot Yields and Chemical Heats of Combustion for Common Materials Based on Bench Scale Calorimeter Testing in Well Ventilated Conditions Derived from Data Published by Tewarson [12] and Klote and Milke [13]

Material	Y_s (kg/kg)	ΔH_{ch} (MJ/kg)
Phenolic foam	0.002	10
Fiberboard[2]	0.008	14
Wool 100%	0.008	19.5
Wood (red oak)	0.015	12.4
Wood (hemlock)	0.015	13
Wood (Douglas fir)[2]	0.018	13.3
PMMA	0.022	24.2
Polypropylene	0.059	38.6
Polyethylene (PE)	0.06	38.4
Silicone	0.065	10.6
Nylon	0.075	27.1
Polyethylene foam[3]	0.076	34.2
Silicone rubber	0.078	10.9
Polyester[3]	0.09	20.1
ABS	0.105	30
PE with 25% chlorine	0.115	22.6

Material	Y_s (kg/kg)	ΔH_{ch} (MJ/kg)
Polyurethane foam (rigid)[3]	0.118	16.9
Polystyrene	0.164	27
Polyvinylchloride (PVC)	0.172	5.7
Polyurethane foam (flexible)	0.188	17.6
Polystyrene foam[3]	0.194	25.5

Figure 5 Soot Yields for Common Materials Based on Bench Scale Calorimeter Testing in Well Ventilated Conditions Derived from Data Published by Tewarson [12] and Klote and Milke [13]



1.4.3 Characteristic Smoke / Soot Yields for Ventilation-controlled Design Fires

Soot yields are very sensitive to ventilation and exposure to heat and, in ventilation control conditions typical of many *fully developed fires*, substantial increases in the soot yields will occur whilst the effective heat of combustion (chemical heat of combustion) will reduce due to a reduction in the combustion efficiency.

Tewarson [12] reported correlations for variations in soot yields and chemical heats of combustion relative to the local equivalence ratio (Φ) which is defined as:

$$\Phi = S\dot{m}''A/\dot{m}_{air}$$ Equation B2.4

Where:

Φ = equivalence ratio

S = stoichiometric mass air-to-fuel ratio (g/g)

$\dot{m}''$ = mass loss rate (g/m^2.s)

A = exposed area of material burning (m^2)

$\dot{m}_{air}$ = mass flow of air (g/s).

The correlations have been used to convert the well-ventilated soot yields and chemical heats of combustion to values under ventilation-controlled conditions ($\Phi \geq 1$) for typical materials. The results are summarised in Table 9 and Table 10.

Table 9 Soot Yields for Common Materials for Differing Ventilation Conditions Derived Using Correlations from Bench Scale Experiments, Soot yield Y_s (kg/kg), Reported by Tewarson [12]

Material	Φ<<1	Φ=1	Φ=2	Φ=3
Wood (red oak)	0.015	0.018	0.028	0.034
Polystyrene	0.165	0.202	0.330	0.416
Nylon	0.077	0.085	0.105	0.120
Polyethylene (PE)	0.061	0.071	0.098	0.117

Table 10 Heats of Combustion for Common Materials for Differing Ventilation Conditions Derived Using Correlations from Bench Scale Experiments, ΔH_{ch} (MJ/kg), Reported by Tewarson [12]

Material	Φ<<1	Φ=1	Φ=2	Φ=3
Wood (red oak)	12.4	11.4	8.3	6.2
Polystyrene	27	24.9	18.2	13.6
Nylon	27.1	24.9	18.2	13.6
Polyethylene (PE)	38.4	35.3	25.9	19.3

A characteristic value for the soot yield of 0.14kg/kg is specified in New Zealand Verification Method CV2 for post-*flashover* (ventilation controlled) *design fires* and may be an appropriate indicative value if the constitution of a *fire load* is unknown. New Zealand Verification Method CV2 is silent with respect to adjustments to the heat of combustion. A value of 50% of the well-ventilated value (i.e. 10MJ/m^2) should be considered if a more appropriate value cannot be identified for the derivation of a smoke production rate from a prescribed HRR.

1.4.4 Limitations

In many cases it is considered reasonable to use the general values suggested above subject to agreement with the PBDB stakeholders but in situations where the contents are not well mixed, the values for the worst-case contents should be used.

However, ventilation and exposure of materials to radiant flux in building fires can vary substantially from those in the bench-scale measurement and will affect the chemical heat of combustion, soot and species yield values. The application of these inputs is further complicated by coalescing and agglomerating of particles and deposition that may also occur. It is therefore necessary to adopt a cautious approach supported by good engineering judgement.

Since the FSVM adopts a comparative approach, the sensitivity to the selected inputs will tend to be less than an absolute study because for most applications similar inputs will be adopted for the proposed *Performance Solution* and the *reference building*. Notwithstanding this, a sensitivity study can be undertaken if there is a concern that the ranking of the building solutions may change if an alternative yield or heat of combustion is adopted.

1.5 Radiative Fraction

The radiative fraction of the heat released from a fire plume depends on the type of fuel, combustion efficiency, soot concentration and the diameter of burning surface area, amongst other things. The corresponding term “convective fraction” is also in common use and for most cases, the sum of the radiative and convective fractions equals 1.

Typical convective fractions for exposed solid fuels or liquid fuels burning in a pool lie in the range of 0.6 to 0.7 according to ISO 16734:2006[15] and the International Fire Engineering Guidelines[16] indicate that the convective HRR is typically 70% of the total HRR.

Karlsson and Quintiere [17] indicate that “the energy losses due to radiation from the flames are typically in the order of 20 to 40% of the total energy release rate. The higher of these values are valid for the sootier and more luminous flames, often from fuels that burn with a low combustion efficiency. The convective energy release rate fraction is therefore often in the range of 0.6 to 0.8.

For pool fires, Drysdale [18] observed that the radiative fraction reduced for pools with large diameters and could be as low as 0.1 compared to typical values of 0.2 to 0.4 below 5 m diameter.

For general applications, the following fractions should therefore be considered unless the specific configuration for a particular project requires more detailed consideration:

Radiative fraction - 0.3

Convective fraction - 0.7.

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Data Sheet B3: Design Fires – Typical Calculation Methods for Fully Developed Design Fires

Group B Data Sheets provide typical input data and guidance relating to the derivation of *design fires* and supplements guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC *DTS* provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building.*

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group B Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet (B3) provides details of typical calculation methods for defining *design fires* for *fully developed fires* and should be read in conjunction with the FSVM Handbook and other Group B Data Sheets which include:

- Data Sheet B1: Design fires - overview
- Data Sheet B2 Design fires – characteristic input data
- Data Sheet B4: Design fires – simple design fires for comparison of wall and ceiling linings.

Design fires for Horizontal Fire Spread between Buildings (HS) and Vertical Fire Spread (VS) scenarios are not addressed since these scenarios are predominantly addressed in *Verification Methods* CV1 to CV3.

This Data Sheet focusses on the content relating to the FSVM and in particular areas where a level of standardisation with respect to the selection of input data and / or analysis methods is considered useful. It does not cover all relevant inputs and appropriate methods of analysis.

Data Sheet B3 Contents

Version	Date	Data	Comments
B3-1	Dec 2018	B3	Final draft for comment
B3-2	Jun 2019	B3	Draft for publication.

1.1 Calculation Methods for Fully Developed Design Fires

1.1.1 Typical Applications

Fire exposure during the fully developed (and decay stages) are commonly quantified to:

- provide inputs for the design of elements of construction to resist the spread of fire and / or maintain *structural adequacy* when exposed to a *fully developed fire*
- provide inputs for modelling the spread of fire and smoke through a building
- provide inputs for modelling the spread of fire to adjacent buildings.

The focus of the empirical calculation methods described in this Data Sheet is to provide inputs for the design of elements to resist exposure to *fully developed fires*.

1.1.2 Design of Elements of Construction and Services to Resist Exposure to Fully Developed Fires

Whilst most technical *fire safety engineering* literature focusses on the behaviour of the structure when exposed to *fully developed fires*, other elements of construction or services may need to maintain their function when exposed to a *fully developed fire* through part or all of a fire scenario. Typical examples include non-loadbearing elements providing fire compartmentation and essential services such as cables providing power and control / communication functions during a fire emergency. This Data Sheet has therefore focussed on the derivation of fully developed *design fires* for modelling the performance of a broad range of elements of construction and services that may be required to resist *fully developed fires*.

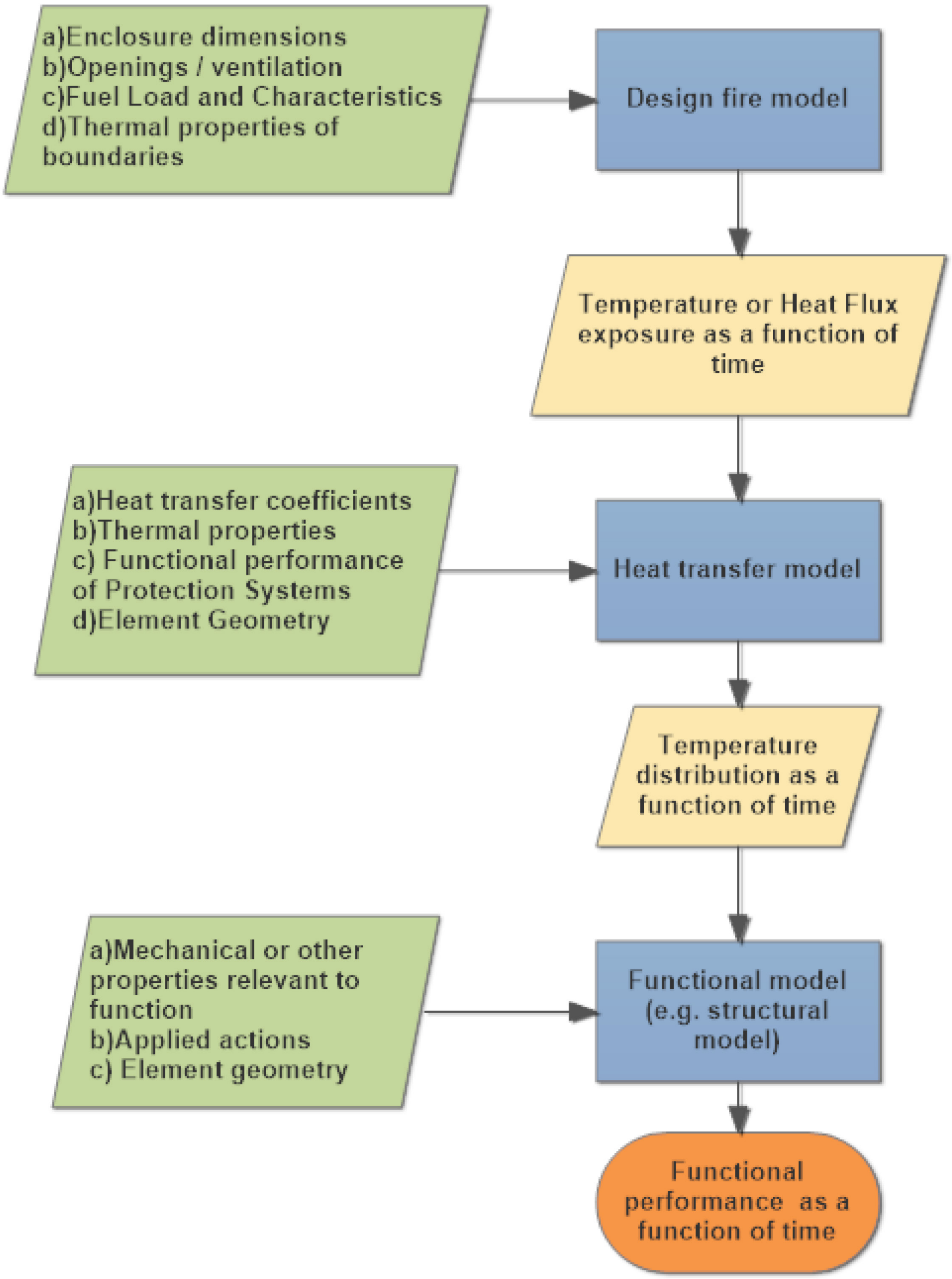
The detailed design of elements of construction and services to resist exposure to a *fully developed fire* typically involves a three-stage process:

- calculation of the fire exposure (Stage 1)
- calculation of the thermal response of the element of construction to the fire exposure (Stage 2)

- calculation of the impact of the thermal response on the ability of an element or structure to perform its design function (Stage 3).

The process is shown in Figure 1 which is a further development of a basic flow chart originally prepared for structural design by Buchanan[2].

Figure 1 Typical Process for Modelling the Performance of Elements of Construction and Services Exposed to Fully Developed Fire Scenarios



This Data Sheet relates to the *design fire* model stage which derives the enclosure conditions which can then be used as an input for subsequent analysis of the functional performance of an element, service or part or all of a structure.

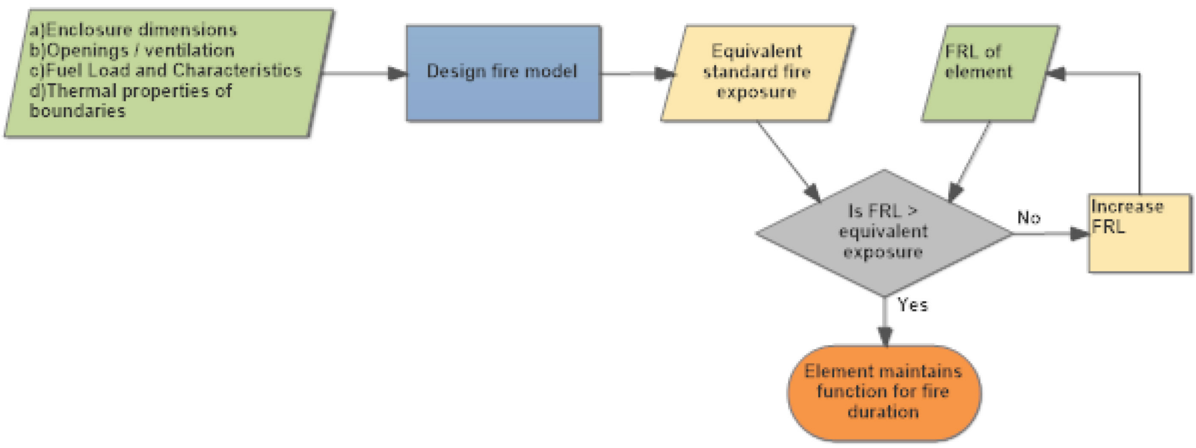
Section 1.3 describes a typical empirical method for deriving the exposure of elements in terms of enclosure temperatures during the fully developed and decay phases of a *design fire* based on parametric curves.

It is possible to consolidate some or all the above calculation stages depending on the application under consideration.

For example, the time equivalence concept can consolidate all three stages by relating the expected real fire exposure to a time of exposure to the standard (AS 1530.4) heating regime. Using this approach, the fire exposure (or fire severity) can be expressed as a single equivalent fire resistance test time assuming all the *fire load* has been consumed. The FRL of the element is then compared to the equivalent fire resistance exposure time to determine if the element or service is likely to satisfy its design function throughout the fire scenario.

The time equivalence design process is shown in Figure 2.

Figure 2 Time Equivalence Design Process



Time equivalent approaches are discussed further in Section 1.2.

1.1.3 Selection of Methods of Analysis

Calculation methods and the corresponding inputs should be selected having regard for the analysis being undertaken.

Simple consolidated calculation methods such as those based on equivalent fire resistance exposure are particularly suited to buildings that have clearly defined *fire loads* and ventilation conditions and a fire safety strategy has the necessary controls to maintain these conditions throughout the life of the building.

Major advantages of this approach include:

- availability of simple hand calculations yielding a single parameter (equivalent fire resistance test exposure time) to define the fire severity
- the required performance of elements of construction or services can be clearly specified in terms of required FRLs and verified using a *Standard Fire Test* (AS 1530.4) providing product developers and suppliers with a clearly defined pathway to obtaining appropriate evidence of suitability
- many structural design codes such as AS 4100 [3], AS 3600 [4] and AS 1720.4 [5] provide methods for calculating the FRL of elements of construction.

Major disadvantages include:

- modelling the behaviour of a structure, element of construction or critical service through a fire scenario cannot be undertaken. Hence the failure time in the actual fire scenario is not predicted and the method cannot therefore be used for predicting if evacuation or *fire brigade* intervention occurs prior to collapse.
- the impact of different heating rates and maximum temperatures that may be more representative of the scenario under consideration is not directly determined. Therefore, if elements or services are sensitive to heating rates and / or maximum temperatures unconservative estimates of the functional performance of the elements or services during a fire scenario could be made using this method.
- most of the empirical formulae have been predominately validated using steel members protected by non-reactive insulating systems that remained in place throughout the heating period. The method should therefore be applied with caution to structural protection systems that progressively fall away such as intumescent protection systems and exposed timber systems, etc.

- the empirical formulae have not been fully validated for systems including service penetrations, doors and lightweight loadbearing and non-loadbearing structures.

In the context of the FSVM which requires comparison of the proposed *Performance Solution* against a *reference building* having similar layouts there would need to be a clear justification for any variations to the *fire load* or ventilation conditions between the two building solutions being compared and any variations would need to be agreed by the relevant stakeholders during the PBDB process. Also, the FSVM requires the likely conditions faced by the *fire brigade* personnel to be determined at the time of arrival and throughout the remainder of a fire scenario.

Therefore, in many FSVM applications (and other NCC assessment methods) a time-temperature relationship or other time dependent fire exposure regime should be derived. Such an approach also allows account to be taken of any compensatory measures introduced into the proposed *Performance Solution*. A typical method (European Standard EN 1991-1-2: 2002 Annex A) that defines parametric heating curves is described in Section 1.3.

1.2 Time Equivalence Approaches for Defining Fire Severity

1.2.1 Introduction

There are several empirical calculation methods in common usage for estimating the fire severity of a *fully developed fire* (including the decay stage) in terms of an equivalent time of exposure to the standard heating regime which in Australia is defined in AS 1530.4 [6].

The time equivalence is generally calculated, based on the *fire load*, ventilation conditions and some of the methods include modifications to account for the thermal properties of the enclosure boundaries.

1.2.2 Application of European Standard EN 1991-1-2: 2002 Annex F

Annex F of EN 1991-1-2 : 2002[7] is a typical example of a time equivalence approach and is described below with guidance relating to its application under the FSVM.

General limitations:

(a) The EN standard states that the method is material dependent and that it is not applicable to composite steel and concrete or timber constructions.

This limitation is included because the correlations were developed based on heat transfer to protected steel members as is the case with many of the other similar methods. As observed by Kirby et al [8] the method is also sensitive to the thickness and thermal properties of protection applied to the steel members as well as the critical temperature adopted.

The impact of these limitations when used as a comparative approach as required by the FSVM will tend to be reduced and the broader application to protected structural members and other elements of construction may be able to be justified on a case by case basis, subject to agreement with the PBDB stakeholders. This approach is consistent with the following statement provided in the IFEG 2005 [9]:

"Although the time-equivalence formula is based on the thermal performance of insulated steel members, it is widely used for fire containment and structural performance of many different materials. The formula contains a number of assumptions and approximations, but is generally accepted as capable of providing a first-order estimate of the required performance".

(b) Annex E of EN 1991-1-2 must not be used for the determination of the *fire load* densities when using the Annex F method to determine the time equivalence when determining compliance with the NCC[1].

This restriction is applied because Appendix E includes a series of adjustments to account for the floor area, potential characteristics of the *fire load*, fire protection measures in place and *fire brigade* intervention. These matters should be addressed specifically as part of the fire engineering analysis process and therefore the use of Appendix E is not appropriate when using the FSVM method.

(c) The standard indicates that the method should be limited to *fire compartments* with mainly cellulosic type *fire loads*.

(d) The standard indicates that if there are no horizontal openings, the floor area of the enclosure should be less than 100m^2. The validity of the assumption of uniform temperature conditions throughout enclosures that are much larger than 100m^2 or that are long and narrow has been questioned but to some extent this has been addressed by Kirby et al [8].

Kirby et al undertook a range of experiments with compartments approximately 22.855 m long x 5.595 m wide (128 m^2) x 2.75 m high with openings in one 5.595 m face and included a square enclosure 5.595 m x 5.595 m (31.3 m^2) x 2.75 m high. In most cases the enclosure walls and ceilings were lined with ceramic fibre to minimise heat losses with the intention of simulating an approximate 45 m slice through a building of unrestricted length.

Some of the key findings from the Kirby study were:

- Modifications should be made to the conversion factor (k_b) which takes account of the thermal properties of the enclosure.
- Reducing the area of the enclosure by ¼ reduced the average equivalent standard fire resistance exposure time by 25% for the same fire loading and ventilation conditions. Calculation based on small compartment geometries would therefore provide conservative answers.

It is therefore reasonable to consider application of the method to enclosures with floor areas larger than 10 0m^2 on a case by case basis when adopting the comparative approach required by the FSVM subject to a satisfactory justification of the approach being documented and agreed with the PBDB stakeholders.

Equations and Inputs:

The equivalent time of standard fire exposure is calculated using the following relationship:

$t_{e,d} = q_{fd}.k_b.w_f$ (minutes) Equation B3.1

where

$t_{e,d}$ = the equivalent time of exposure

q_{fd} = *design fire* load density per unit floor area, MJ/m^2 (note the contribution from elements of construction should be added to the characteristic value for the occupancy)

k_b = conversion factor which takes account of the thermal properties of the enclosure, min/(MJ/m^2) [Thermal properties expressed as b = $(k\rho c)^{1/2}$ – J/m^{2}s$^{1/2}$K] Refer Table 1 for k_b values.

Table 1 Values for Conversion Factor to Take Account of Thermal Properties, k_b – min /(MJ/m^2)

Description	b>2500	720≤b≤2500	b<720	General
Example floors (from Kirby)	Normal weight concrete	Normal weight concrete	Lightweight concrete	All
Example walls (from Kirby)	Uninsulated steel and concrete	Blockwork Plasterboard - no insulation	Plasterboard with mineral fibre insulation	All
EN 1991-1-2:2002	0.04	0.055	0.07	0.07
Kirby recommendation	0.05	0.07	0.09	0.09

Note: for enclosures larger than 100 m^2 k_b values recommended by Kirby should be adopted and the ventilation factor (w_f) should be calculated using Equation 3.4.

w_f = ventilation factor which can be calculated using one of the following relationships:

(a) If there are no horizontal openings and the floor area of the enclosure is less than 100 m^2, the following relationship is permitted to be used for the determination of the ventilation factor:

$$w_f = O^{-1/2} \cdot {A_f}/{A_t} \qquad \text{Equation B3.2}$$

and the opening factor is calculated using the following relationship:

$$O = A_v \cdot (h_{eq})^{1/2}/A_t\,,\; 0.02 < O < 0.20 \qquad \text{Equation B3.3}$$

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

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

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

A_f =floor area of enclosure - m^2.

(b) Where there are horizontal openings, the following relationship should be used:

$$w_f = \left({6.0}/{H}\right)^{0.3} \cdot \left[0.62 + \frac{90(0.4-a_v)^4}{(1+b_v.a_h)}\right],\; \geq\; 0.5 \qquad \text{Equation 3.4}$$

where H is the height of the *fire compartment* - m

A_h = area of horizontal openings in the roof

$\alpha_v = A_v / A_f$ for $0.025 \leq \alpha_v \leq 0.25$

$\alpha_h = A_h / A_f$

$b_v = 12.5 (1 + 10\alpha_v - \alpha_v^2) \geq 10.0$.

For other definitions refer option A.

1.3 Time-temperature Regime for Fully Developed Fires (Stage 1)

1.3.1 Introduction

There are numerous closed form models that can be used to generate time / temperature regimes for post *flashover* compartment fires based on the *fire load*, ventilation and thermal properties of boundaries, many of which have been reviewed by Hurley [10]. The calculation of the time / temperature regime is the first stage in assessing the performance of an element of construction or structure (see Section 2.2).

The method presented in Annex A of EN 1991-1-2:2002 [7] is considered a good example because it has also been codified, used extensively and can be incorporated into a spread sheet.

1.3.2 Application of European Standard EN 1991-1-2: 2002 Annex A

The method is described below with guidance relating to its application under the FSVM.

General limitations:

(a) EN 1991-1-2:2002 states the temperature-time curves are valid for *fire compartments* up to 500 m^2 of floor area, without openings in the roof and for a maximum compartment height of 4 m.

(b) The method assumes that the specified *fire load* of the compartment is completely burnt out.

However, because a time-temperature history is derived, it is possible with additional analysis to determine scenario times to failure of elements of construction and to take account of interventions allowing the interactions between various parts of a fire safety strategy to be evaluated.

(c) Annex E of EN 1991-1-2 must not be used for the determination of the *fire load* densities when using the Annex F method to determine the time equivalence when determining compliance with the NCC[1].

This restriction is applied because Appendix E includes a series of adjustments to account for the floor area, potential characteristics of the *fire load*, fire protection measures in place and *fire brigade* intervention. These matters should be addressed specifically as part of the fire engineering analysis process and therefore the use of Appendix E is not appropriate when using the FSVM method.

(d) The standard indicates that the method should be limited to *fire compartments* with mainly cellulosic type *fire loads*.

Equations and Inputs:

The temperature-time curves in the heating phase are given by:

$$\theta_g = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*})$$ Equation 3.5

where:

θ_g =enclosure gas temperature - °C

t* = a fictitious time given by:

$$t^* = t.\Gamma$$ Equation 3.6

where:

t = time (h).

Note: If fire is fuel controlled t* should be derived using equation Eq 3.12.

The modification factor Γ is calculated using the following equation:

$$\Gamma = \frac{(O/b)^2}{(^{0.04}/_{1160})^2}$$ Equation 3.7

$$b = (\rho c\lambda)^{1/2},\ \text{J/m}^2\text{s}^{1/2}\text{K},\ 100 \le b \le 2200$$

ρ = density of bounding enclosure -kg/m^3

c= specific heat of boundary enclosure – J/kgK

λ= thermal conductivity of boundary of enclosure – W/mK.

$$O = {A_v (h_{eq})^{1/2}}/{A_t}, \; m^{1/2}, \; 0.02 \le O \le 0.20$$ Equation 3.8

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

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

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

The maximum temperature θ_{max} occurs when $t^* = t^*_{max}$.

$$t^*_{max} = t_{max}\Gamma$$ Equation 3.9

$$t_{max} = \text{greater of } \left(\left[0.2 \cdot q_{t,d} \cdot \frac{10^{-3}}{O}\right], t_{lim}\right)$$ Equation 3.10

where t_{lim} expressed in hours = 0.417 for a slow growth rate; 0.333 for a medium growth rate and 0.25 for a fast growth rate.

$q_{t,d}$ is the design value of the *fire load* density related to the **total surface area** (A_t) of the enclosure. The following limits should be observed; 50 ≤ q_{td} ≤ 1 000 - MJ/m^2.

$q_{t,d}$ can be derived from the more commonly used, ($q_{f,d}$) - *fire load* density related to the surface area of the floor –(A_f) using:

$$q_{t,d} = q_{f,d} \cdot {A_f}/{A_t}, \text{ -MJ}/m^2$$ Equation 3.11

The fire is:

- ventilation controlled if $\left[0.2q_{t,d} \cdot 10^{-3}/O\right] \ge t_{lim}$; and
- fuel controlled if $0.2q_{t,d} \cdot 10^{-3} > \left[0.2q_{t,d} \cdot 10^{-3}/O\right]$

If the fire is fuel controlled:

$t^* = t\,\Gamma_{lim}$ Equation 3.12

instead of the value derived from Eq 3.6

with:

$$\Gamma_{lim} = \left(\frac{O_{lim}}{b}\right)^2 \Big/ \left(\frac{0.04}{1160}\right)^2$$ Equation 3.13

$O_{lim} = {0.1q_{t,d} \cdot 10^{-3}}/{t_{lim}}$ Equation 3.14

If O_{lim} > 0.04, qt,d<75 and b<1160; Γ_{lim} in Eq 4.9 has to be multiplied by k where;

$k = 1 + \left(\frac{O-0.04}{0.04}\right) \cdot \left(\frac{q_{t,d}-75}{75}\right) \cdot \left(\frac{1160-b}{1160}\right)$ Equation 3.15

During the cooling phase, the temperature is assumed to decrease linearly at one of three rates specified below:

$\Theta_g = \Theta_{max} - 625(t^* - t^*_{max}X),\ t^*_{max} \geq 0.5\text{hours}$ Equation 3.16a

$\Theta_g = \Theta_{max} - 250(3 - t^*_{\max})(t^* - t^*_{max} \cdot X),\ 0.5 > t^*_{max} > 2\text{ hours}$ Equation 3.16b

$\Theta_g = \Theta_{max} - 250(t^* - t^*_{max}X),\ t^*_{max} \geq 2\text{ hours}$ Equation 3.16c

where t* is given by equation 4.2.

$t^*_{max} = \left(\frac{0.2q_{t,d}10^{-3}}{O}\right) \cdot \Gamma$ Equation 3.17

X = 1.0, if $t_{max} > t_{lim}$, (ventilation-controlled case) or

X = $t_{lim}\,\Gamma / t_{max}$, if $t_{max} = t_{lim}$ (fuel-controlled case)

Calculation of “b” for enclosure surfaces with different layers of material:

If $b_1 < b_2$, $b=b_1$

If $b_1 > b_2$, a limit thickness s_{lim} is calculated for the exposed material according to:

$s_{lim} = \left(\frac{3600t_{max}\lambda_i}{c_i\rho_i}\right)^{1/2}$ Equation 3.18

where t_{max} is obtained from equation 4.6

If $s_1 > s_{lim}$ then $b = b_1$ Equation 3.19a

If $s_1 < s_{lim}$ then $b = s_1/s_{lim}\, b_1 + (1 - s_1/s_{lim})\, b_2$ Equation 319b

where:

the index, 1, represents the layer directly exposed to the fire, the index, 2, the next layer….

s_i is the thickness of layer i

$$b_i = (\rho_i c_i \lambda_i)^{1/2}$$

ρ_i is the density of the layer i

c_i is the specific heat of the layer i

λ_i is the thermal conductivity of the layer i

Calculation of "b" for different b factors in walls ceilings and floors:

$$b = \frac{(\sum(b_j A_j))}{A_t A_v}$$

where:

A_j is the area of enclosure surface j, openings not included

b_j is the thermal property of enclosure surface j.

1.4 Thermal or Functional Response of an Element of Construction (Stage 2)

There are a range of calculation methods available varying from empirical correlations for simple lumped thermal mass calculations to finite element analysis. The method should be appropriate for the application under consideration. This is the second stage of calculation mentioned in Data Sheet C8.

It may be appropriate to either directly apply experimental / fire test data where the heating regime is representative of the case under consideration or the impact of variations can be predicted based on fire engineering principles.

Variations in material properties and quality of installations should be accounted for. In some scenarios this may require consideration of major variations representing unauthorised substitution of materials, for example, to determine the robustness of the overall fire safety strategy. Further guidance is outside the scope of this Data Sheet.

1.5 Capability of an Element or Structure to Perform Its Design Function (Stage 3)

Similarly, there are a range of calculation methods varying from simple hand calculations using prescribed critical temperatures or char rates to detailed structural analysis methods using finite element analysis and material properties which vary with temperature. This is the third stage of calculation described in Data Sheet C8.

In cases where it is necessary to consider the interaction of elements of construction to determine that the structure has adequate robustness, detailed modelling of the whole or major parts of the structure under a range of fire scenarios may be required.

It may also be appropriate to either directly apply experimental / fire test data where the heating regime and applied loads are representative of the case under consideration or the impact of variations can be predicted based on fire engineering principles.

The impact of thermally induced deflections and stresses should be considered. Obtaining input and advice from a structural engineer with regards to the structural performance of the assessed element or design should also be considered.

Further guidance is outside the scope of this Data Sheet.

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9. ABCB, International Fire Engineering Guidelines Edition 2005. 2005, Australian Building Codes Board: Canberra.

10. Hurley, M.J., Evaluation of models of fully developed post-flashover compartment fires. Journal of Fire Protection Engineering, 2005. **15**(3): p. 173-197.

Data Sheet B4 Design Fires – Simple Design Fires for Comparison of Wall and Ceiling Linings

Group B Data Sheets provide typical input data and guidance relating to the derivation of *design fires* and supplements guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

Use of information from Group B Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet (B4) provides details of simple *design fires* for comparison of wall and ceiling fires and should be read in conjunction with the FSVM Handbook and other Group B Data Sheets which include:

- Data Sheet B1 Design Fires - Overview
- Data Sheet B2 Design Fires – Characteristic Input Data
- Data Sheet B3 Design Fires – Typical Calculation Methods for Fully Developed Design Fires.

Design fires for Horizontal Fire Spread between Buildings (HS) and Vertical Fire Spread (VS) scenarios are not addressed since these scenarios are predominantly addressed by *Verification Methods* CV1 to CV3.

This Data Sheet focusses on the content relating to the FSVM and in particular areas where a level of standardisation with respect to the selection of input data and / or analysis methods is considered useful. It does not cover all relevant inputs and appropriate methods of analysis.

Data Sheet B4 Contents

Version	Date	Data	Comments
B4-121	Dec 2018	B4	Final draft for comment
B4-2	Jun 2019	B4	Draft for publication

1.1 Applications for Simple Design Fires for Comparison of Wall and Ceiling Linings

The simple *design fires* described in this Data Sheet have been derived for use with the FSVM for comparisons of wall and ceiling linings where the *group numbers* determined in accordance with AS 5637 vary within an enclosure(s) for a proposed *Performance Solution* and the *reference building*.

A typical example would be a *Performance Solution* that proposes the use of Group 3 wall and ceiling linings for an application where the corresponding *reference building* requires Group 2 linings.

The impact of a change in *group number* may include modifications to:

- the *fire growth* rate and as a consequence:
    - the time to *flashover*
    - the time to untenable conditions
- the proportion of *fully developed fires*
- the *fire load* and as a consequence
    - fire severity.

The most relevant FSVM[1] Scenario is:

Internal Surfaces (IS). Interior surfaces are exposed to a growing fire that potentially endangers occupants.

However, if there is an impact on the growth rate, the proportion of *fully developed fires* and the *fire load*, the *design fires* for the following FSVM scenarios may also require modification:

- Blocked Exit (BE). A fire blocks an evacuation route
- Unoccupied Enclosure Fire (UT). A fire starts in a normally unoccupied room and can potentially endanger a large number of occupants in another room
- Horizontal Spread (HS). A *fully developed fire* in a building exposes the external walls of a neighbouring building
- Vertical Spread (VS). A fire source exposes a wall

- Challenging Fire (CF). Worst credible fire in an occupied space
- Robustness Check (RC). Failure of a critical part of the *fire safety systems*
- Structural Stability (SS). Building does not present risk to other properties in a fire event
- Fire Brigade Intervention (FI). Consider *fire brigade* intervention
- Unexpected Catastrophic failure (UF). A building must not unexpectedly collapse during a fire event.

The PBDB stakeholders should consider the appropriateness of the use of the simple *design fires* described in this Data Sheet on a case by case basis to determine if they are suitable for the proposed application or whether a more detailed analysis of *fire growth* and spread is required. The considerations and conclusions drawn should be documented in the PBDB report.

1.2 Reference Design Scenario

The reference *design scenario* is based on ignition of an item in the corner of a room that burns at a constant rate of 100kW for a period of 10 minutes before increasing to 300kW for a further 10 minute period unless the fire spreads to involve the wall and ceiling linings. This *design scenario* is closely aligned to ISO 9705[2] Fire tests - full-scale room test for surface products.

Group numbers determined in accordance with AS 5637[3] are used to determine the extent of the involvement of the linings and a growing t-squared *design fire* is assigned based on the time for the total *heat release rate* inclusive of the burner output to exceed 1000kW.

The proportion of fires that this scenario relates to should be derived from analysis of fire statistics.

This is consistent with the approach described in ISO/TR 11696-2:1999[4] which states-

> *"Based on assessment of real fires, four categories of growth rate curves have been defined for design used in fire safety engineering. Test-data from cone calorimeter (ISO5560), room / corner test (ISO 9705) and*

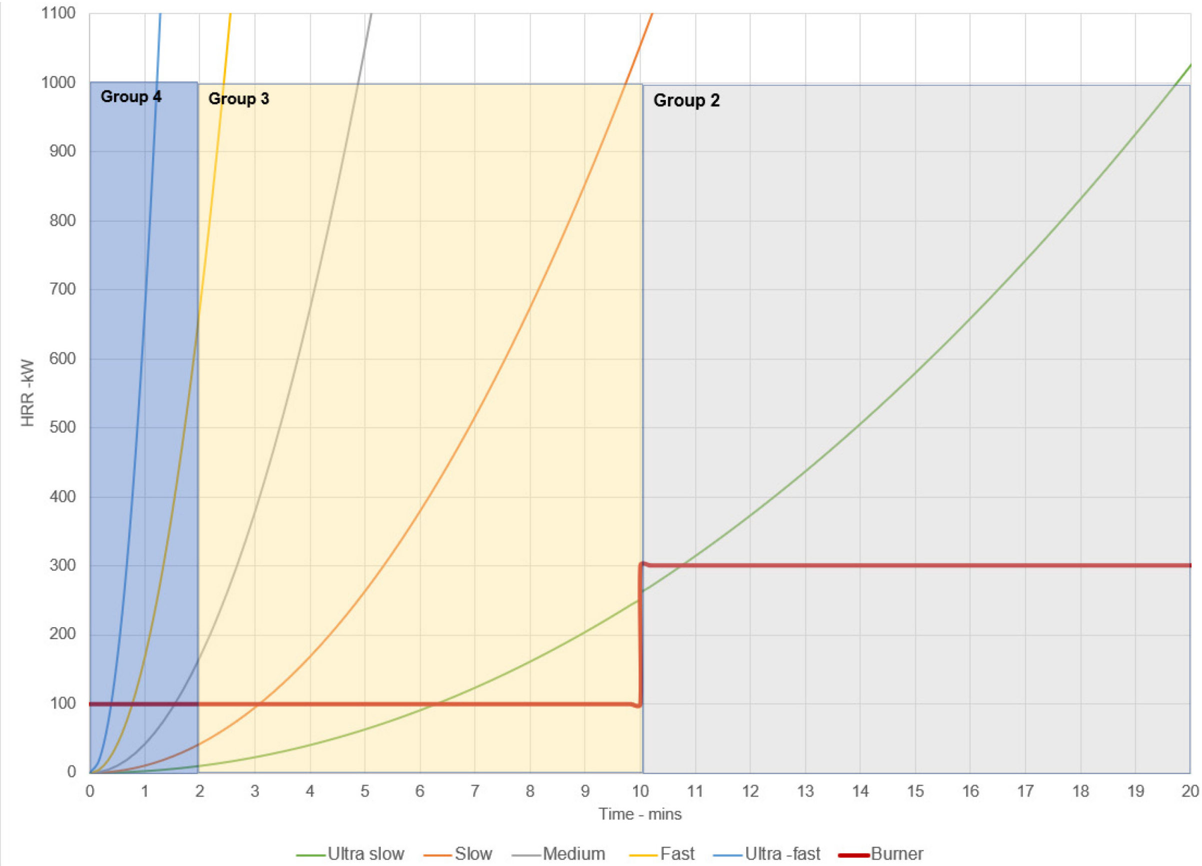
realistic full-scale tests may be used to assist the fire engineer in allocating the performance of a building product to one of these design growth curves."

"This decision would be made in a pragmatic way depending on the availability of suitable test data and use of heat release rate data in this way is not intended to be the sole way in which fire hazards can be quantified within the enclosure of fire origin. Hazards may also be identified from the statistics of real fires, personal knowledge and experience (probabilistic methods) and from reports of fire tests (deterministic methods)".

1.3 Selection of T-Squared Design Fires

The ultra-fast, fast, medium and slow t-squared growth curves are plotted in Figure 3. Also plotted is an ultra slow fire with a growth parameter of 0.0007 kJ/s^3 and the output from the gas burner specified in ISO 9705. The range of times to *flashover* for the various Group Classes are also shown. Group 1 applies if *flashover* does not occur during the 20 minute test.

Figure 1 Plot of T-Squared Fires, ISO 9705 Burner Heat Release Rate and AS 5637 Group Number Classifications



The following are based on observation from Figure 3:

- The ultra-fast fire applies to Group 4 linings.
- The fast, medium and slow growth rates cover the range of Group 3 linings. The fast and medium growth rates can be assumed to apply to Group 3 linings with the slow growth rate applied to Group 2 linings (see below).

The following process can be adopted to determine whether the medium or fast growth rates should be applied to a Group 3 wall and ceiling lining:

1. Where the proposed lining system is known and the time to *flashover* (1MW HRR) when subjected to an ISO 9705 test is also known, a system specific growth rate can be derived based on the time for the HRR to exceed 1MW in the test or the following “standard” growth rates adopted:
   - if the time to 1MW HRR in an ISO 9705 test is ≥ 5 minutes – medium
   - if the time to 1MW HRR in an ISO 9705 test is < 5 minutes – fast.

2. Where generic Group 3 wall and ceiling linings are required for the *reference building*, a medium growth rate should be assumed.
3. Where generic Group 3 wall and ceiling linings are specified for the proposed *Performance Solution*, a fast growth rate should be assumed.

   (This approach is expected to yield conservative results for most scenarios).

The slow growth rate is closely aligned with the interface between Group 2 and Group 3 materials and is therefore assumed to define the quickest growth rate permitted for a Group 2 lining.

An ultra-slow fire has been defined with a *fire growth* parameter selected to coincide with the interface with Group 1 and 2 linings and is therefore assumed to define the quickest growth rate permitted for Group 1 linings.

Table 1 Design T-Squared Fires, Group Numbers and Fire Growth Parameters

Group number	Fire description	Fire Growth Parameter α (kJ/s^3)	Approx. time to reach 1055kW - s
1	Ultra-slow	0.0007	1228
2	Slow	0.00293	600
3 (ref bld.)[1]	Medium	0.0117	300
3 (PS)[2]	Fast	0.047	150
4	Ultra-fast	0.188	75

Note 1: Medium fire should be selected for a generic Group 3 linings in the *reference building.*

Note 2: Fast fire should be selected as generic Group 3 linings for a *Performance Solution.*

1.4 Application of T-Squared Fires and Other Data Required for Comparison of Linings

1.4.1 Interventions

The t-squared fires for the scenario described in this Data Sheet should be modified as appropriate to address various interventions (e.g. *automatic* suppression).

1.4.2 Fire Load Adjustments

The characteristic *fire loads* described in Data Sheet B2 exclude contributions from structural elements and wall and ceiling linings and therefore the contribution from these elements of construction to the *fire load* should be added.

Group 1 lining materials are expected to provide a minimal contribution.

Group 2 to 4 linings can be expected to contribute to the *fire load* which should be calculated using appropriate material properties if known or nominal values agreed with the stakeholders during the PBDB process if the lining materials are not specified.

Unless otherwise justified it should be assumed that all *combustible* wall and ceiling linings are consumed in a *fully developed fire* without intervention and the *fire load* should be adjusted accordingly.

Note: Reductions in the heat of combustion due to the fire retardants and reductions in lining materials involved if self-extinguishment occurs can be considered if fully justified to the satisfaction of the stakeholders during the PBDB process.

1.4.3 Modification to the Proportion of Fully Developed Fires

Approximate estimates can be made of the proportion of fires that do not progress beyond 100kW and 300kW based on the extent of fire spread and assuming a typical rate of heat release. A *heat release rate* of 250kW/m^2 is commonly assumed for many occupancies.

The proportion of these fires that are likely to occur in the corners and against the walls can be used to conservatively estimate the proportion of fires to which the *design fire* applies (i.e. fires that spread to involve wall and ceiling linings).

If interventions do not occur before *flashover*, the proportion of *flashover* fires should be modified to account for potential increases due to fire spread over linings.

The *design fire* distributions for other FSVM scenarios should be adjusted as well as the Internal Spread (IS) scenario.

1.5 References

1. ABCB, National Construction Code 2019 - 2019.

2. ISO, ISO 9705 Fire tests - Full-scale room test for - surface products. 1993, International Standards Organisation: Geneva.

3. Standards Australia, AS 5637.1 Determination of Fire Hazard Properties. 2015: Sydney Australia.

4. ISO, ISO/TR 11696-2 Uses of reaction to fire test results - Part 2 Fire hazard assessment of construction products. 1999, ISO: Switzerland.

GROUP C

DATA SHEETS

Data Sheet C1 Effectiveness of Fire Safety Systems - Overview

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C1, provides a general overview of the effectiveness of fire protection systems and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

Data Sheet C2 Sprinkler System Effectiveness

Data Sheet C3 Detector Effectiveness

Data Sheet C4 Active Smoke Control System Effectiveness

Data Sheet C5 Smoke Barrier Effectiveness

Data Sheet C6 Fire Barrier Effectiveness

Data Sheet C7 Smoke and Fire door Effectiveness

Data Sheet C8 General Methods for Conversion of Fire Resistance Times.

Data Sheet C1 Contents

Version	Date	Data	Comments
C1-1	Jan 2019	C1	Initial draftraft for comment
C1-2	Jun 2019	C1	Draft for publication

1.1 Effectiveness of Fire Protection Systems

1.1.1 Definitions of Effectiveness

There are varying definitions of reliability, efficacy and effectiveness or similar terms that are used in the fields of *fire safety engineering*, risk engineering and medical sciences depending on the application and this can cause confusion.

Thomas[2] defined effectiveness as a combination of two factors, efficacy and reliability where efficacy is the degree to which a system achieves an objective given that it operates and reliability is the probability that the system operates when required.

Hall[3] adopted a similar approach but using different terminology when considering the performance of sprinklers in the US experience as detailed below:

- % sprinklers operated effectively – equivalent of Thomas definition of effectiveness
- % sprinklers operated – equivalent to Thomas definition of reliability
- % sprinklers effective if they operated – equivalent of Thomas definition of efficacy.

Some of the above definitions require further refinement when applied to passive systems since the term “operate” may not be applicable except for applications such as fire dampers and fire doors with hold open devices. In these cases a performance distribution may be defined as described in the relevant Data Sheets.

The definitions from Thomas have been modified as detailed below to provide flexibility for application to a broad range of fire protection systems and are applicable throughout the Group C Data Sheets.

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system, etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*
- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance

- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

1.1.2 Structural Reliability and Reliability Indices

The concept of structural reliability is broadly applied to structural design predominately for design under ambient temperature conditions as described in the ABCB Structural Reliability Handbook [4]. The handbook indicates that reliability is used as a means for verification of strength of structures subjected to known or foreseeable types of actions such as permanent, imposed, wind, snow and earthquake. As such, it involves a consideration of structural actions and resistance. It means that the levels of workmanship and quality control are assumed to be maintained in accordance with current standards and practice and appropriately accounted for in the resistance model. Structural reliability can be quantified by failure probability (p_F) or reliability index (β).

Consideration has been given to the application of structural reliability approaches to the performance of structures under fire conditions for over two decades (e.g. Wong [5], Hopkin et al [6]). Generally, these approaches have not included consideration of gross defects such as the probability of substitutions or omissions of structural fire protection but focussed on variations in *fire load*, ventilation conditions and in some but not all instances, material properties.

Therefore, in most cases, estimates of structural reliability and reliability indices can only provide an indication of the **efficacy** of fire protected members based on the definition adopted in the Group C Data Sheets unless the potential for gross and other defects are specifically considered. This can be significant since gross defects are most likely to cause premature failures prior to evacuation of a building.

1.1.3 Comparison of Definitions

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison of data.

Table 1 Comparison of Some Definitions

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability[1]	% sprinklers operated	N/A

1.2 Governance of Building Works and Safety Within Buildings

The effectiveness of fire protection systems is influenced throughout the building lifecycle by a broad range of factors.

The scope of the NCC[1] is broadly limited to providing minimum design requirements and the definition of requirements for evidence of suitability that materials and components comply with the requirements of the design and the NCC.

The States and Territories, amongst other things, are responsible for regulating building works within their jurisdictions. Building Acts and Regulations also address to varying extents the maintenance of fire protection systems through the life of a building and requirements for the upgrading of buildings. Since these activities can significantly impact on the reliability and efficacy of fire protection systems through the life of a building, it is necessary to take these factors into account.

Reminder

For the purposes of deriving the estimates in the Group C Data Sheets it has been assumed that the fire protection systems will, as a minimum be designed, installed, commissioned and maintained in accordance with the relevant Australian Standards or equivalent throughout the life of the building and be replaced at the end of their design life. It has also been assumed that adequate oversight is provided to minimise the risk of non-compliant construction occurring.

These assumptions should be made when determining the effectiveness of systems within the *reference building* for comparison with the proposed *Performance Solution* since they reflect the intent of the NCC.

It is noted that there have been significant problems ensuring effective compliance with, and enforcement of, the NCC leading to diminishing public confidence that the building and construction industry can deliver compliant, safe buildings which will perform to the expected standards over the long term as noted by Shergold Weir [7].

Whilst there is broad support to implement the recommendations made in the Shergold Weir report [7] it will be some time before this can be achieved. Therefore, the effectiveness of fire protection systems should be specifically addressed as part of the *Performance Solution*.

Reminder

Requirements to ensure the estimated effectiveness of fire protection systems should be included in the Performance- Based Design Report (PBDR) and / or a document such as a Fire Safety Handbook referenced by the PBDR.

1.3 Derivation of Fire Protection System Effectiveness

1.3.1 Estimating Reliability

Typically, the reliability of a fire protection system can be estimated based on one or a combination of the following approaches:

- Historical data
- Fault tree / event tree analysis
- Technical literature
- Expert judgement including Delphi approaches.

It is necessary to clearly define the performance level consistent with the system specification to determine the reliability since this will impact on the approach adopted for analysis in addition to the availability of data.

For example, except in marginal cases it is possible to determine if a smoke alarm should have operated and did not and since smoke alarms are common within dwellings, there is a substantial volume of available historic data. Therefore, a greater emphasis can be placed on historic data.

For structural fire protection systems after a fire event capable of threatening the structure it can be difficult to determine with confidence, the condition of the element prior to the fire and the exposure of an element during the fire without a detailed analysis. This is further complicated because an unprotected element of construction can have a significant inherent fire resistance and interventions are likely to occur during a fire event reducing the fire duration to such an extent that failure of the element does not occur. Thus, the use of historical data is of limited value and a greater reliance has to be placed on expert judgement.

Specific details of the approach adopted for derivation of reliability are provided in each Data Sheet.

1.3.2 Estimating Efficacy

It is necessary to clearly define the system and objective under consideration before determining the efficacy of a system.

For example, Thomas[2] adopted an objective of life safety in a study of the effectiveness of fire safety components and systems based on historic data.

For the development of *Performance Solutions* greater flexibility is generally required and it is often more appropriate to relate the objective to the performance of a specific fire protection system or combination of related fire protection systems rather than the total *fire safety system* for the building. Specific or combinations of related fire protection systems have generally been adopted for determination of efficacy in the Group C Data Sheets.

1.3.3 Time Dependency

In many instances the performance objective will be time dependent and relate to the timing of other events during a *design scenario* which introduces a further complexity when estimating reliability and efficacy.

When undertaking a quantified risk assessment, it may be possible to incorporate performance distributions or specify characteristic values.

1.4 References

1. ABCB, National Construction Code 2019 2019.

2. Thomas, I.R., Effectiveness of fire safety components and systems. Journal of Fire Protection Engineering, 2002. **12**(2): p. 63-78.

3. Hall, J.R., US Experience with sprinklers. 2013: National Fire Protection Association. Fire Analysis and Research Division.

4. ABCB, Handbook - Structural Reliability. 2015, Australian Government and States and Territories of Australia: Canberra.

5. Wong, J.K.S., Reliability of Structural Fire Design, in School of Engineering. 1999, University of Canterbury: Christchurch.

6. Hopkin, D., et al. Applicability of ambient temperature reliability targets for appraising structures exposed to fire. in 2nd International Conference on Structural Safety under Fire and Blast Loading. 2017.

7. Shergold, P. and B. Weir, Building confidence: improving the effectiveness of compliance and enforcement systems for the building and construction industry across Australia. 2018, Department of Industry Innovation and Science.

Data Sheet C2 Effectiveness of Wet Pipe Automatic Fire Sprinkler Systems

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C2, addresses Sprinkler System Effectiveness, and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1, provides a general overview of the effectiveness of fire protection systems
- Data Sheet C3 Detector Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness
- Data Sheet C5 Smoke Barrier Effectiveness

- Data Sheet C6 Fire Barrier Effectiveness
- Data Sheet C7 Smoke and Fire door Effectiveness
- Data Sheet C8 General Methods for Conversion of Fire Resistance Times.

Data Sheet C2 Contents

Version	Date	Data	Comments
C2-1	Jan 2019	C2	Initial draft for comment
C2-2	Jun 2019	C2	Draft for publication

1.1 Definitions of Effectiveness

1.1.1 General Definitions

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification

- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*
- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

1.2 Definitions of Sprinkler System Effectiveness

The following definitions have been selected in relation to sprinkler system effectiveness, but it is noted that depending upon the matters under consideration other definitions could be adopted.

Sprinkler System Efficacy is defined as the % of events where an operating sprinkler system contains and controls a fire until the *fire brigade* can arrive and complete extinguishment.

Note: This is consistent with the NFPA data element for % sprinklers effective if they operated[2, 3]. It is generally accepted that under these circumstances, *flashover* will not occur, and the fire is unlikely to spread beyond the room of fire origin. The maximum fire size can be estimated based on the number of heads operating (refer section 1.4.3).

Sprinkler System Reliability is based on the fire events where the fire is considered large enough to activate a sprinkler and is defined as the % of events where the sprinkler system operated.

Note: Under this definition it should be assumed that the sprinkler system, if it does not operate, will have no impact on the *fire growth* and will not activate an *automatic* alarm.

Effectiveness is taken as the product of the Efficacy and Reliability expressed as a %.

1.3 Applicable Australian Standards

The general estimates for sprinkler system effectiveness included in this Data Sheet assume wet pipe sprinkler systems designed, installed, commissioned and maintained in accordance with the following standards as appropriate:

- AS 2118.1 Automatic fire sprinkler systems — General systems
- AS 2118.4 Automatic fire sprinkler systems — Sprinkler protection for accommodation buildings not exceeding four storeys in height
- AS 2118.6 Automatic fire sprinkler systems − Combined sprinkler and hydrant systems in multistorey buildings
- AS 1851 – 2012 Routine service of fire protection systems and equipment.

The design, installation and commissioning should have been undertaken based on the edition prescribed by the NCC at the time of installation.

Note: Where analysis is being undertaken on a building using an existing *automatic* fire sprinkler system, the operational status and adequacy of the design should be verified and a decision taken as to the applicability of the general estimates of system effectiveness provided in this Data Sheet.

1.4 Effectiveness Estimates

1.4.1 General Estimates

The FSVM uses a comparative approach rather than an absolute approach which in some cases can reduce the sensitivity of the results to estimates of effectiveness. For example, if the same *automatic* fire sprinkler system forms part of the fire safety strategy for the *reference building* and proposed *Performance Solution* the outcomes are expected to be less sensitive than a fire safety strategy where a proposed *Performance Solution* introduces an *automatic* fire sprinkler system that is not part of the strategy for the *reference building*.

If there is no more appropriate data for a specific application, the typical values from Table 2 should be adopted and a sensitivity analysis undertaken with the high and low values subject to the agreement of the PBDB stakeholders.

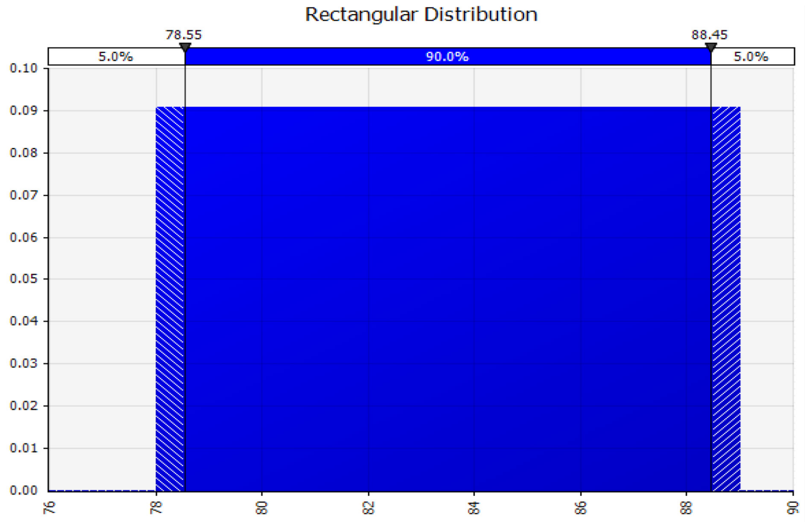
Table 2 Typical Design Value for Australian Sprinkler Systems

NCC Building Class	Reliability (Typical)	Efficacy (Typical)	Effectiveness: Typical	Effectiveness: Low	Effectiveness: High
Residential 2, 3 and 4	95%	97%	92%	87%	97%
General 5, 6, 7a, 8 & 9	90%	96%	86%	81%	91%
Storage 7b	84%	97%	83%	78%	89%

Where more detailed probabilistic analyses are being undertaken the following options can be considered:

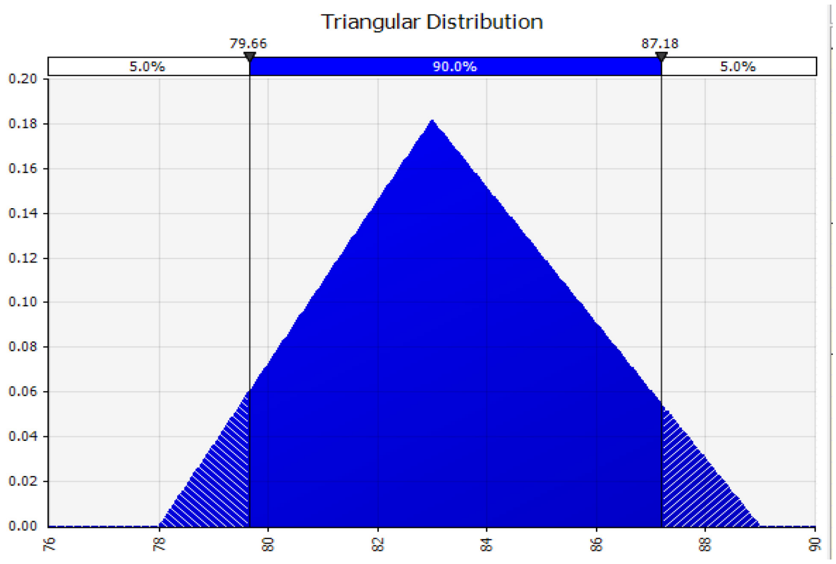
1. Assume a rectangular (uniform) distribution between the low and high estimates.

Figure 1 Illustration of a Rectangular Distribution



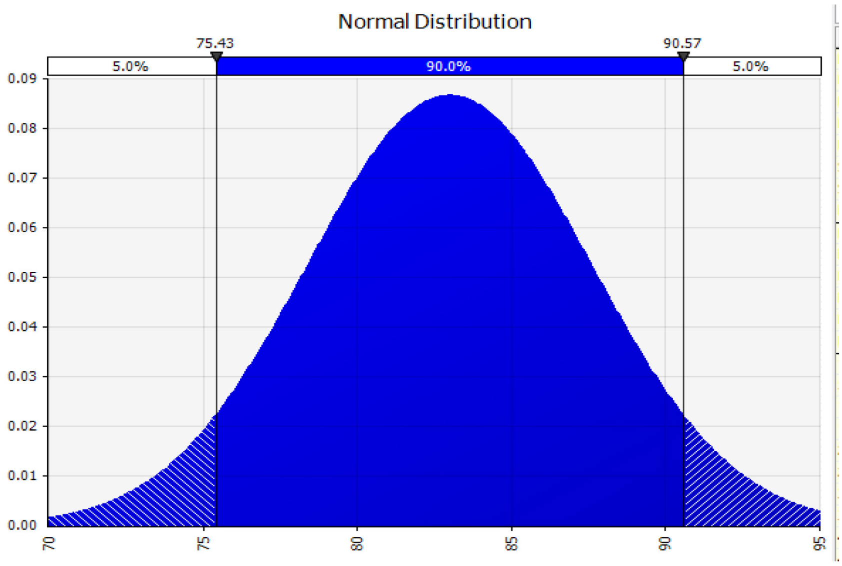
2. Assume a triangular distribution with the highest frequency at the typical value.

Figure 2 Illustration of a Triangular Distribution



3. Assume normal distribution with a mean of the typical value and a standard deviation of 4.6% (based on the recommendation of Frank et al [5]). Note the normal distribution may require truncating or an alternate distribution adopted for higher reliabilities to ensure the assumed distribution does not exceed a value of 100%.

Figure 3 Illustration of a Normal Distribution



1.4.2 Evaluating Enhancements to Automatic Fire Sprinkler Systems

Some of the major factors that reduce the effectiveness of *automatic* fire sprinkler systems are identified in Appendix A.1. There are opportunities to enhance the reliability of systems by, for example, introducing monitored control valves to provide a facility to isolated limited areas where works need to be undertaken and to provide an indication of the status of the valve.

Potential improvements in the effectiveness of the system under these circumstances would normally be quantified based on a component-based study. Typical failure rate data for components are provided in Moinuddin and Thomas [6] and Frank et al [7].

Due to the uncertainty involved in some of the estimated failure rates and human factors involved in the installation, maintenance and operation of the systems, component-based studies should not be used exclusively without comparison to system-based fire data as recommended by Frank et al[7].

For both the *reference building* and any proposed *Performance Solution* appropriate skill and diligence are expected to be employed to the design, installation, commissioning, and maintenance of the system, throughout the life of the building.

These requirements should be reflected in the fire safety strategy and fire safety handbook developed for the project and relevant design documentation.

It is expected that to enhance the effectiveness of a sprinkler system some modifications to the sprinkler system design will be required rather than solely relying on enhanced human factors.

1.4.3 Efficacy Estimates

The efficacy estimates provided in Table 2 are based on the requirement that an operating sprinkler system contains and controls a fire until the *fire brigade* can arrive and complete extinguishment.

Based on the above requirement it is considered reasonable to assume the following performance will be achieved if the efficacy criteria are satisfied:

- *flashover* will be prevented
- the fire is unlikely to spread beyond the room of fire origin
- the fire will not activate more than the design number of sprinklers prescribed by the design standard for the particular hazard or the number of heads within the enclosure whichever is the lesser.

Therefore, if the maximum fire size of a controlled fire needs to be estimated the maximum HRR can be determined as the HRR at the time of activation of the last sprinkler head within the assumed area of operation or the room.

Other efficacy criteria can be adopted depending upon the analysis being undertaken but the efficacy estimates in Table 2 will require adjustment.

Typical examples of alternative efficacy criteria could be:

- *automatic* suppression of a fire
- maintaining tenable conditions within the enclosure of fire origin for a prescribed period
- maintaining tenable conditions in an enclosure adjacent to the enclosure of fire origin
- preventing fire spread to an adjacent building.

Under these circumstances it would be necessary to refer to experimental data and / or sprinkler head listing criteria and undertake a system-based study using fire data to derive appropriate efficacy estimates.

A.1 Appendix: Background Information

A.1.1 International Review

Due to the relatively small population size and hence small number of buildings with *automatic* fire sprinkler systems present in Australia and limited reporting of recent sprinkler performance, insufficient statistical data from Australia is available to reliably estimate the efficacy of *automatic* fire sprinkler systems.

Although there are some national differences with respect to design, installation and maintenance practices the general principles are consistent, and many components are manufactured for a global market, therefore it is considered reasonable to refer to international data but noting that there may be some variations in installation, maintenance and monitoring practices.

A detailed review of sprinkler system effectiveness studies was prepared by Frank et al [7] and published in 2013. Frank generally adopted the same definitions of effectiveness, efficacy and reliability that have been adopted for the Group C Data Sheets. The study was a comprehensive review of existing published data and previous reviews which included both:

- system-based studies (based on fire data)
- component-based studies (typically fault tree analyses).

The estimated effectiveness from system-based studies ranged from 70% (Juneja [8]) to 99.5% (Marryatt [9]), however, these outlying estimates were not consistent with the definition of effectiveness adopted in the Frank study explaining the large variance from the remaining reviewed studies. If these two outliers are set aside the range of estimates in the reviewed data vary from 81.3% to 98.8% with the higher estimate being based on US Department of Energy facilities for the period 1955-2003 which may not be comparable to typical building stock. The next highest effectiveness estimate from the reviewed group of studies was 97%.

A.1.2 Analysis of NFPA Sprinkler Data

More recent data relating to the effectiveness of sprinkler systems has been published in the US for the periods 2007-2011(Hall [2]) and 2010-2014 (Ahrens[3]).

The results are summarised in Table 3 and Table 4 respectively. These tables have then been consolidated into three Building Groups; Residential (having a higher than average effectiveness) Storage (having a lower than average effectiveness) and a General group for other occupancies with the outcomes shown in Table 3.

Table 3 Reliability and Effectiveness of Wet Pipe Sprinkler System in the US for Various Property Uses for the Period 2007-2011, 1) Number of Fire / Year and 2) Percentage of Qualifying Fires (adapted from Hall 2013[2])

Property Use	1)Sprinklers present	Too small to activate equipment	Coded as confined	Qualifying fires[1]	2)Equipment operated (A)	System effective if operated (B)	Equipment operated effectively (AxB)
All public assembly	2,810	480	1,770	550	92%	95%	88%
Eating or drinking establishment	1,330	250	750	330	93%	94%	88%
Educational property	1,810	390	1,250	170	87%	97%	84%
Health care property	2,900	590	2,020	300	87%	98%	85%
All residential	26,280	2,240	20,370	3,670	95%	97%	92%
Home (including	21,060	1,470	16,670	2,920	95%	97%	92%

Property Use	1)Sprinklers present	Too small to activate equipment	Coded as confined	Qualifying fires[1]	2)Equipment operated (A)	System effective if operated (B)	Equipment operated effectively (AxB)
apartment)							
Hotel or motel	1,680	320	1,080	270	91%	97%	89%
Store or office	3,680	970	1,710	990	91%	97%	88%
Grocery or convenience store	740	220	340	170	90%	96%	87%
Department store	410	160	140	110	87%	97%	85%
Office	980	220	600	170	90%	98%	88%
Manufacturing facility	2,160	570	670	920	91%	94%	86%
All storage	570	120	200	260	85%	98%	83%
Warehouse excluding cold store	320	70	80	170	86%	97%	84%
All structures	42,520	5,680	29,690	7,150	92%	96%	89%

Note: Qualifying fires are fires where data on the sprinkler performance was available and the fire was considered large enough to activate the sprinklers.

Table 4 Reliability and Effectiveness of Wet Pipe Sprinkler System in the US for Various Property Uses for the Period 2010-2014, 1) Number of Fires/ Year and 2) Percentage of Qualifying Fires, (adapted from Ahrens 2017 [3])

Property Use	1)Sprink-lers present	too small to activate or	Confined fires	Quali-fying	2)Equipm ent operated	Effective if operated	Equipme nt operated effective
All public assembly	3,080	490	2,030	560	90%	96%	86%
Eating or drinking establishment	1,450	250	860	340	93%	95%	89%
Educational property	1,670	370	1,140	160	90%	96%	86%
Health care property	2,740	530	1,940	270	88%	97%	85%
All residential	28,050	2,320	21,970	3,770	96%	96%	93%
Home (including apartment)	21,760	1,680	16,730	3,350	95%	96%	91.2%
Hotel or motel	1,850	320	1,240	300	91%	99%	89.8%
Store or office	3,710	890	1,860	950	90%	96%	87%
Grocery or convenience store	830	210	460	170	89%	95%	85%
Department store	380	140	140	110	89%	99%	88%
Office	980	200	620	160	91%	98%	89%
Manufacturing facility	2,010	520	650	850	91%	94%	86%
All storage	510	100	150	250	82%	96%	79%
Warehouse excluding cold store	290	60	80	160	84%	97%	82%
All Structures	43,540	5,540	30,790	7,210	89%	96%	86%

Note 1; Qualifying fires are fires where data on the sprinkler performance was available and the fire was considered large enough to activate the sprinklers

Table 5 Reliability Efficacy and Effectiveness Data Based on US Statistics for 2007 to 2014

NCC Building Class	Reliability	Efficacy	Effectiveness
Residential 2, 3 and 4	95%	97%	92%
General 5, 6, 7a, 8 & 9	90%	96%	86%
Storage 7b	84%	97%	83%

A significant degree of judgement is necessary in determining the efficacy of a system after a fire event. However, the US data summarised in Table 3 and Table 4 provide consistent efficacy values across all occupancies. Larger variability in the reliability estimates can be observed in the data. Reliability estimates also require judgement in determining the proportion of fires that were of insufficient size to activate the sprinkler system.The main reasons for the effectiveness of a system being compromised as reported by Ahrens [3], are summarised in Table 6.

Table 6 Causes that Reduce the Effectiveness of Automatic Fire Sprinkler Systems

Cause	% of reliability failures (failure to operate)	% of efficacy failures (ineffective after operation)	% of effectiveness failures (combined failure)
System shut-off	59	N/A	40
Water did not reach the fire	N/A	51	17
Manual intervention	17	3	13
Not enough water discharged	N/A	30	10
Lack of maintenance	10	4	8
System components damaged	7	7	7
Inappropriate system for type of fire	7	6	6

A.1.3 Australian Studies

As part of a Fire Code Reform Centre (FCRC) project examining Fire Safety in Shopping Centres (Bennetts et al [10]) the following data relating to fires in retail premises protected by sprinkler systems in NSW was obtained for the period 1987-1995 and is summarised in Table 7.

Table 7 NSW Sprinkler Performance in Retail Premises 1987-1995 from Bennetts et al [10]

Sprinkler operation	No of fires	% of qualifying fires[1]
Performance not indicated	7	N/A
Fire too small	182	N/A
Operated but performance not reported	2	N/A
Extinguished the fire	146	64
Prevented spread	71	31
Operated but did not prevent spread	6	3
Should have operated but did not	5	2
Total	419	100

Note: % of qualifying fires was calculated from the 228 fires where data on the sprinkler performance was available and the fire was considered large enough to activate the sprinklers.

The available sample is relatively small approximating to one year of the NFPA data for sprinkler protected retail premises, but the following approximate estimates can be obtained which is at the higher end of the data from international sources:

- reliability 98%
- efficacy 97%
- effectiveness 95%.

The FCRC report also identified that the careful design and management in use of sprinkler systems can substantially improve the reliability of the systems by reducing the unprotected areas of the building whilst the sprinklers are isolated for repair, maintenance and refurbishment and the time for which they are unprotected. The adoption of monitored valves also provides an indication if a system is inadvertently left isolated.

A more recent component-based analysis of the reliability of wet-pipe sprinkler systems in Australian high-rise office buildings has been undertaken (Moinuddin and Thomas [6]). The analysis was based on a comprehensive survey of sprinkler systems in high-rise office buildings to determine the reliability of various components of such systems in Australia. Based on the survey data, fault tree analysis was used to estimate the reliability of these sprinkler systems. The survey was based on twenty-six buildings supplemented by data from overseas surveys.

Fault trees were developed based on the designs found in usual practice rather than the designs just complying with the Australian codes with the minimum requirements and the component reliability data expected to reflect better than average maintenance practices since participation in the survey was voluntary and organisations with a greater focus on safety are considered more likely to participate.

A range of reliability values for the sprinkler systems was calculated and varied from 86.6% to 97.9%. Sprinkler zone shut off during tenancy changes and out of specification sprinkler heads appeared to be the main factors that may lead to a sprinkler system failure. The fault tree analysis indicated that by installing a zone isolation valve for each floor, the failure probability of a sprinkler system can be reduced between 10% to 63% of its original failure value.

The estimated general occupancy sprinkler system reliability from Table 5 is 90% which lies within the range for high-rise office buildings calculated using the fault tree analysis.

A.2 References

1. ABCB, National Construction Code 2019 2019.

2. Hall, J.R., US Experience with sprinklers. 2013: National Fire Protection Association. Fire Analysis and Research Division.

3. Ahrens, M., U.S. Experience with Sprinklers. 2017, US: National Fire Protection Association.

4. Standards_Australia, AS 1851 2012 Routine service of fire protection systems and equipment. 2012, SAI Global: Sydney.

5. Frank, K., M. Spearpoint, and N.J.F.t. Challands, Uncertainty in estimating the fire control effectiveness of sprinklers from New Zealand fire incident reports. 2014. **50**(3): p. 611-632.

6. Moinuddin, K. and I. Thomas, Reliability of sprinkler system in Australian high rise office buildings. Fire safety journal, 2014. **63**: p. 52-68.

7. Frank, K., et al., A review of sprinkler system effectiveness studies. Fire science reviews, 2013. **2**(1): p. 1.

8. Juneja, C.S., Analysis of Ontario fires and reliability of active fire protection systems. 2005, Carleton University.

9. Marryatt, H.W., Fire, a century of automatic sprinkler protection in Australia and New Zealand, 1886-1986. 1988.

10. Bennetts, I., et al., Fire Safety in Shopping Centres: Final Research Report. 1998: Fire Code Reform Centre.

Data Sheet C3 Effectiveness of Detection and Alarm Systems

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C3, addresses, Detection and Alarm System Effectiveness and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1 General overview of the effectiveness of fire protection systems
- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness
- Data Sheet C5 Smoke Barrier Effectiveness
- Data Sheet C6 Fire Barrier Effectiveness

- Data Sheet C7 Smoke and Fire door Effectiveness
- Data Sheet C8 General Methods for Conversion of Fire Resistance Times

Data Sheet C3 Contents

Version	Date	Data	Comments
C3-1	Jan 2019	C3	Initial draft for comment
C3-2	Jun 2019	C3	Draft for publication

1.1 General Definition of Effectiveness

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*

- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

1.2 Types of Detection Systems

The following types of common building fire detection and alarm systems are considered in this Data Sheet:

(a) Residential smoke alarm systems consisting of smoke alarms complying with AS 3786[2] and powered from the consumer mains source with battery backup and interconnected as required in NCC 2019 [1].

Battery powered smoke alarms have also been included because of the large numbers still in use.

These are generally self-contained systems within a dwelling or *sole-occupancy unit* (SOU).

(b) General fire detection, warning, control and intercom systems complying with AS 1670 Part 1[3] and referenced secondary standards used for smoke and heat detection system components. These types of systems tend to be used for larger multi-residential buildings, commercial, industrial and institutional buildings.

Since the system configurations, application and availability of relevant fire statistics vary considerably between residential smoke alarm systems and general fire detection, warning, control and intercom systems, different approaches have been adopted in Sections 1.3 and 1.4.

1.3 Residential Smoke Alarm Systems

1.3.1 General Description

The residential smoke alarm systems considered in this section are interconnected self-contained systems within a single-dwelling or SOU with the objective of raising a local alarm if activated to alert the occupants of the single dwelling or SOU. Under current NCC requirements, the smoke alarms must comply with AS 3786 [2], be powered from the consumer mains source, and interconnected where there is more than one alarm.

The NCC DTS provisions require smoke alarms to be installed on or near the ceiling in any storey containing bedrooms, between each part of the SOU containing bedrooms and the remainder of the SOU and where bedrooms are served by a hallway, in that hallway; and in any other storey not containing any bedrooms.

1.3.2 Categorising Smoke Alarm System Effectiveness

The following definitions have been selected in relation to smoke alarm system effectiveness.

Smoke Alarm System Efficacy

For the purposes of the Group C Data Sheets, efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification.

There are numerous objectives that could be selected to determine the efficacy of smoke alarm systems depending on the extent occupant response, evacuation and exposure to tenable conditions during a fire emergency are considered. However, some or all these matters may be addressed as part of an occupant response, evacuation and exposure analysis if they are not integrated into the efficacy estimates for the smoke alarm system. Typical examples that could be considered for fire alarm efficacy are summarised below. These criteria assume the probability of sufficient products of combustion reaching the detector to cause activation of a smoke alarm with a sensitivity consistent with the system specification will be determined by fire modelling and are not included in the efficacy estimate.

1. Sound pressure levels above a prescribed limit throughout relevant occupied areas after smoke alarm activation
2. Smoke alarms alert occupants after activation of the smoke alarm
3. Smoke alarms alert occupants and occupants respond after activation of the smoke alarm
4. Reductions in fatalities and injuries if a smoke alarm operates compared to a no alarm case.

The second option, smoke alarms alert occupants after activation of the smoke alarm, has been adopted since supporting fire statistics are available.

Reminder

The efficacy will be estimated from fire statistics and will be a general estimate based on all fires occurring at all times of the day and over the full range of residential occupancies and should not be taken as accurately reflecting the ability to waken any occupant type without regard for their particular characteristics.

The waking effectiveness of alarms varies considerably with factors such as age, presence of alcohol and drugs, background noise, alarm volume and frequency. Detailed investigations were undertaken by Bruck et al [4] and Xiong et al[5] providing useful background information. Duncan [6] carried out experiments in residential settings with a simulated residential alarm placed in the corridor outside bedrooms and determined that in 85% of cases the occupants were alerted but reference should be made to the sample occupant characteristics if applying this data as an alternate efficacy criteria.

Smoke Alarm System Reliability is based on the fire events where the fire is considered large enough and close enough to activate a smoke alarm and is defined as the % of events where a smoke alarm is activated under these circumstances.

Effectiveness is taken as the product of the Efficacy and Reliability expressed as a %.

1.3.3 Estimates of Smoke Alarm System Effectiveness

The FSVM uses a comparative approach rather than an absolute approach which in some cases can reduce the sensitivity of the results to estimates of effectiveness. For example, if the same fire alarm system forms part of the fire safety strategy for the *reference building* and proposed *Performance Solution* the outcomes are expected to be less sensitive than a fire safety strategy where a proposed *Performance Solution* considers variations to the coverage of smoke alarms as part of the strategy for the *reference building*.

If there is no more appropriate data for a specific application the typical values from Table 2 should be considered and a sensitivity analysis undertaken with the high and low values subject to agreement of the PBDB stakeholders. Further information on the data and published literature used as the basis for the estimated values is provided in Appendix A.

As noted in the Senate Legal and Constitutional Affairs References Committee report - Use of Smoke Alarms to Prevent Smoke and Fire Related Deaths [7]:

> *"It is difficult to locate statistics about fire-related incidents in Australian states and territories, and even more challenging to find statistics that can be compared in a meaningful way."*

The majority of the data referenced in Appendix A has therefore been drawn from other countries with similar usage of smoke alarms, mainly the US, UK and NZ.

Table 2 Estimates of Typical Design Value for Australian Smoke Alarm System

NCC Building Class	Reliability (Typical)	Efficacy (Typical)	Effectiveness: Typical	Effectiveness: Low	Effectiveness: High
Battery operated smoke alarms – limited coverage	85%	93%	79%	74%	84%
Interlinked mains powered smoke alarms with battery backup (minimum NCC coverage)	95%	93%	88%	83%	93%
Interlinked mains powered smoke alarms with battery backup full coverage	95%	95%	90%	85%	95%

Note 1. Efficacy is a typical value based on fire statistics from the UK where occupants alerted by other means were identified.

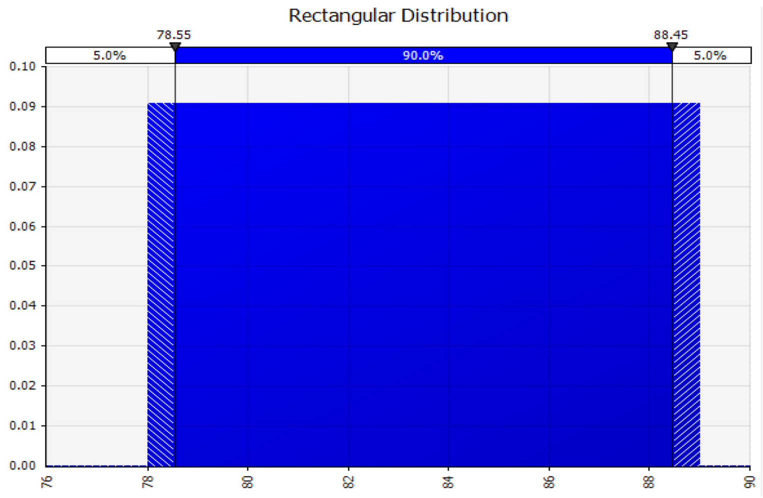
Note 2. If the efficacy is based on initiating a response from sleeping occupants a substantial reduction in the efficacy value may be required depending on the occupant profile. A maximum efficacy under these circumstances of approximately 85% is indicated by the work of Duncan[6] but this will vary with the occupant group under consideration.

Note 3. Higher values for efficacy have been assumed for interlinked smoke alarms with full coverage because the alarm volume would be expected to be higher, particularly within the bedrooms where currently coverage is not mandated in the NCC.

Where more detailed probabilistic analyses are being undertaken the following options can be considered. The graphed distributions are for illustrative purposes only and the values do not correspond to the generic values in Table 2.

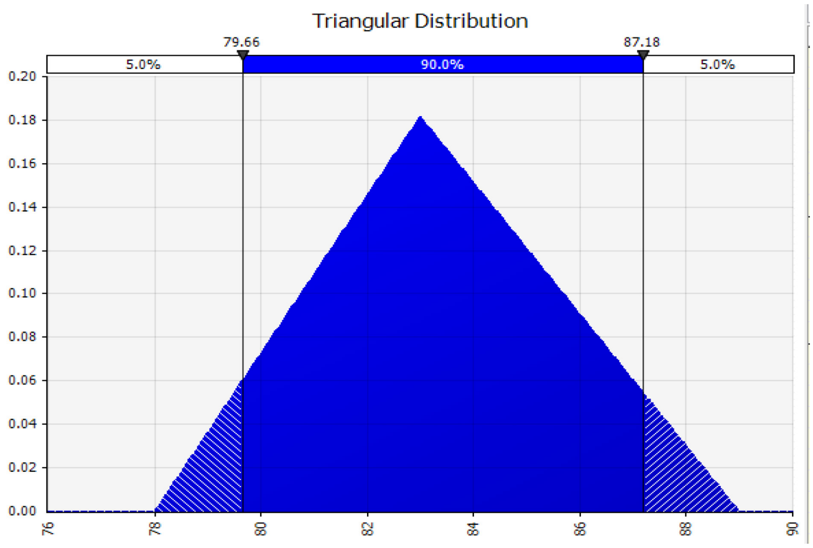
1. Assume a rectangular (uniform) distribution between the low and high estimates.

Figure 1 Illustration of a Rectangular Distribution



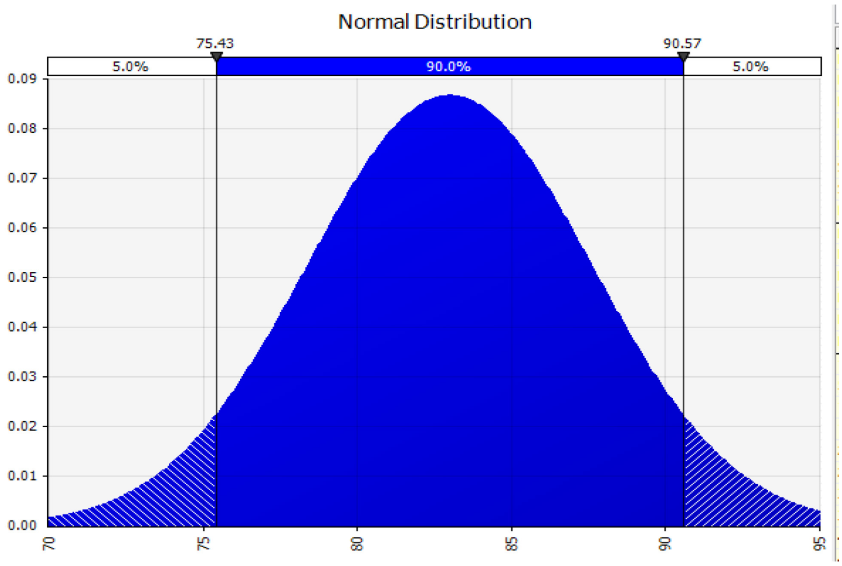
2. Assume a triangular distribution with the highest frequency at the typical value.

Figure 2 Illustration of a Triangular Distribution



3. Assume normal distribution with a mean of the typical value and a standard deviation of 5% (using a similar approach to that recommended by Frank et al [8] for *automatic* sprinkler systems). Note the normal distribution may require truncating or an alternate distribution adopted for higher reliabilities to ensure the assumed distribution does not exceed a value of 100%.

Figure 3 Illustration of a Normal Distribution



1.3.4 Evaluating Enhancements to Automatic Smoke Alarm Systems

Some of the major factors that reduce the effectiveness of smoke alarm systems are identified in Appendix A.1. These can be used to identify opportunities to enhance the effectiveness of the systems and evaluate variations, for example, extending the coverage of the smoke alarm systems within SOUs to include bedrooms.

For both the *reference building* and any proposed *Performance Solution* appropriate skill and diligence are expected to be employed to the design, installation, commissioning and maintenance of the system, throughout the life of the building. These requirements should be reflected in the fire safety strategy and fire safety handbook developed for the project and relevant design documentation.

1.3.5 Efficacy Estimates

The efficacy estimates provided in Table 2 are based on the objective that smoke alarms alert occupants after activation of the smoke alarm.

Thus, the efficacy estimate will approximate to an average value based on fire statistics from all incidents and not an indication of the efficacy for scenarios with sleeping or vulnerable occupants.

If the efficacy is based on initiating a response from all sleeping occupants, a substantial reduction in the efficacy value may be required depending on the occupant profile. A maximum efficacy under these circumstances of approximately 85% is indicated by the work of Duncan[6] but this may require further reduction for some occupant groups.

1.4 General Fire Detection, Warning, Control and Intercom Systems

1.4.1 Overview of Types of General System

General fire detection, warning, control and intercom systems under the NCC DTS provisions are generally required to comply with AS 1670 Part 1 [3] and referenced secondary standards.

The detectors are connected directly or indirectly to a Fire Indicator Panel (FIP). These types of system tend to be used for larger multi-residential buildings, commercial, industrial and institutional buildings. There are a broad range of options and configurations that can be tailored to the specific needs of a building and the systems may interface with other fire protection systems.

Simple overviews of typical general systems are provided below.

1.4.1.1 Conventional Systems

Conventional fire alarm systems comprise one or more zones depending on the size of the building, amongst other things. Each zone is protected by a series of smoke and /or heat detectors wired back as a group via the same cable to a FIP. If smoke or heat is detected, the detector state changes from normal to alarm and the FIP triggers an alarm. The FIP will also indicate the zone in alarm but not the individual detector.

There are many larger existing conventional system installations and this type of system may still be used for buildings with relatively simple layouts. Much of the older data relating to fire detection system reliability is based on this type of system.

1.4.1.2 Addressable Systems

Addressable systems, as the name suggests, allow the individual detector in alarm to be identified because each detector has a unique address. The detectors are wired in a loop and typically the FIP has an LCD so that text messages can be programmed and displayed. High level interfaces can be used to communicate to other *fire safety systems* such as components of active and passive smoke control systems in addition to alarm and intercom systems.

These variations from conventional systems will have an impact on the effectiveness of the fire detection system. For example:

- the use of a communication loop connecting the detectors allows for continual polling to check system integrity and if there is one brake in the cable causing an open circuit the system may still operate (note; a short circuit on the loop will prevent all detectors on the loop operating which can be mitigated by the use of short circuit isolators – this would be expected to enhance the reliability)
- the efficacy of the system may be improved (depending of the objectives used to determine efficacy) by allowing more accurate determination of the source of a fire
- the controlling software and programming of the FIP for a particular site introduce the risks of software / programming errors which may reduce the reliability of the system.

1.4.1.3 Analogue Addressable Systems

An analogue addressable detector has the capability of relaying the exact location of the activated device in a similar manner to an addressable detector but in addition, it will transmit data on the condition of the detector in addition to the fault or alarm signals provided by both the conventional and addressable systems.

The additional information may include:

- identifying dirty detectors, reducing the risk of false alarms
- providing an alert prior to activating the main alarm as the smoke / heat levels increase to allow for rapid intervention.

The additional information provided may improve the efficacy as well as reducing false alarms.

1.4.1.4 Combination Systems

Combinations of the above systems can be consolidated into a single system using appropriate hardware. This is useful when upgrading, expanding or optimising systems for a particular application but will add complexity to the system which should be considered when estimating the system effectiveness.

1.4.2 Interfacing with Other Systems

The fire detection systems commonly interface with other *fire safety systems* through the FIP. Typical examples are described in the following sections.

1.4.2.1 Emergency Warning and Intercom Systems

These can vary from a general alarm system serving the whole building for small simple buildings to multi-zoned evacuation systems that incorporate intercommunication facilities for more complex buildings.

The general alarm system (single zone) can vary from a single tone generator and amplifier to provide alert / evacuation tones only, to more complex systems that provide public address capabilities and visual alarm outputs.

Multi-zoned evacuation systems are used when buildings are split into different zones to facilitate phased evacuations. Each zone is individually controlled and has:

- dedicated speaker systems for evacuation tones and public address and may be supplemented by visual alarms

- warden intercom points to facilitate communication with the head warden are also provided as part of the emergency warning and intercom systems.

1.4.2.2 Active Smoke Management Systems

Typical active smoke management systems include smoke exhaust systems, stair pressurisation systems and zone pressurisation systems.

The FIP needs to communicate with the control panel for the smoke management system which may be achieved by various options including:

- use of control wiring from the FIP connected to the control panel for each fan
- addressable devices located on a dedicated loop run from the FIP which transfer data to the control panels for the fans.

1.4.2.3 Passive Fire and Smoke Management Systems

Typical passive fire and smoke management systems that may interface with the FIP include:

- smoke and fire doors provided with hold open devices that release the doors upon receipt of a signal from the FIP
- smoke dampers and heat / smoke vents operated in response to a signal from the FIP.

1.4.2.4 Automatic Suppression Systems

Automatic suppression systems such as gaseous and foam systems can be activated in response to an alarm signal from a detection system. These types of systems tend to be used for property protection and business continuity rather than compliance with the NCC but could be incorporated as part of a *Performance Solution.*

1.4.2.5 Security Systems

The FIP may interface with parts of the security system to release electric locks or strikes on *exit* doors that are normally locked for security purposes.

1.4.2.6 Monitoring Systems

The FIP may initiate an *automatic* notification to a fire safety dispatch centre.

1.4.3 Common Mode Failures

Since the FIP panel can interact with many other fire protection systems as described above, common mode failures should be considered for scenarios such as the Robustness Check, Structural Stability, Fire Brigade Intervention and Unexpected Catastrophic failure when using the FSVM.

For example, a total failure of the FIP could disable or initiate inappropriate actions from all the systems listed in Section 1.4.2 unless some redundancy or other mitigation methods such as fail-safe facilities are adopted.

1.4.4 Categorising General Fire Detection, Warning, Control and Intercom System Effectiveness

The following definitions have been selected in relation to fire detection system effectiveness, but it is noted that depending upon the matters under consideration it is valid to adopt alternate definitions provided the effectiveness estimates are modified accordingly.

General Fire Detection, Warning, Control and Intercom System Efficacy

For the purposes of the Group C Data Sheets efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification.

There are a number of objectives that could be selected to determine the efficacy of general fire detection, warning, control and intercom systems varying to the extent human factors during a fire emergency and interactions with other fire protection systems are taken into account.

To provide an estimate of the efficacy that is suitable for general application and is not modified to account for one of the many other systems that interface with an FIP the following objective has been selected.

Within the required time for the *design scenario,* the fire is detected and the detection system provides appropriate signals (as defined in the fire safety strategy) to the:

- emergency warning and intercommunication systems
- direct data link or other approved monitoring system to a fire station or fire station dispatch centre
- any other systems as required by the fire safety strategy (e.g. stair pressurisation system, release of *automatic* fire and smoke doors etc).

The efficacy will need to be determined on a case by case basis since it will be a function of the *design fire*, sensitivity of detectors and locations of detectors amongst other things. NFPA 72[9] Appendix B is an example of a document providing guidance on methods for calculating activation times of smoke and heat detectors. The appropriate methods should be selected to address the specific project and be accepted by the PBDB stakeholders.

Fire Detection System Reliability is based on the fire events where the fire is considered large enough and close enough to activate a detector and is defined as the % of events where a detector is activated and the FIP correctly identifies the alarm and forwards an appropriate signal(s) to the interfacing fire protection systems.

Effectiveness is taken as the product of the Efficacy and Reliability expressed as a %.

1.4.5 Estimates of Fire Detection System Effectiveness

Since efficacy is to be estimated on a case by case basis, generic reliability values only will be provided in this section. Efficacy should be derived on a case by case basis as part of the *fire safety engineering* analysis.

There is limited data and substantial variability in values for the reliability of detection systems and this may reflect variations in complexity and details of the design which may impact on the robustness of the system and sensitivity to the quality of installation, commissioning and maintenance.

Appropriate skill and diligence are expected to be employed to the design, installation, commissioning, and maintenance of the system, throughout the life of the building. These requirements should be reflected in the fire safety strategy and fire safety handbook developed for the project and relevant design documentation.

If there is no more appropriate data for a specific application the generic values provided in Table 3 should be considered and a sensitivity analysis undertaken with the high and low values subject to agreement of the PBDB stakeholders. Further information on the data and published literature used as the basis for the estimated values is provided in Appendix A.2.

As noted in the Senate Legal and Constitutional Affairs References Committee report - Use of Smoke Alarms to Prevent Smoke and Fire Related Deaths [7] "*It is difficult to locate statistics about fire-related incidents in Australian states and territories, and even more challenging to find statistics that can be compared in a meaningful way*." The majority of the data referenced in Appendix B has therefore been drawn from other countries with similar usage of smoke detection systems.

Table 3 Typical Design Value for Australian Smoke Detection Systems

Type of Detection System	Reliability: Typical	Reliability: Low	Reliability: High
Simple Addressable System	90%	83%	97%
Complex Addressable Systems	85%	78%	92%
Conventional Systems	80%	73%	87%

The FSVM uses a comparative approach rather than an absolute approach which can reduce the sensitivity of the results to estimates of effectiveness. For example, if the same fire detection and alarm system forms part of the fire safety strategy for the *reference building* and proposed *Performance Solution* the outcomes are expected to be less sensitive than a fire safety strategy where a proposed *Performance Solution* considers variations to the detection systems. In these instances, the generic values may be used but the expected variation to the reliability could be estimated based on a fault tree analysis focussing on the variations.

A.1 Appendix A Background to Smoke Alarm System Estimates

A.1.1 Estimates of Effectiveness Based on UK Fire Statistics

The UK fire statistics used in this section were obtained from the Home Office web site[10].

A.1.1.1 Efficacy of Smoke Alarms

For the purposes of the Group C Data Sheets efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification.

There are a number of objectives that could be selected to determine the efficacy of smoke alarm systems including:

- smoke alarms alerted occupants if the smoke alarms operated
- reductions in fatalities and injuries if a smoke alarm operated
- sound pressure levels above a prescribed limit throughout relevant occupied areas if smoke alarm operated.

The selected objective may vary depending upon the analysis methods selected. The probability that smoke alarms alert occupants has been selected for the UK statistics because the information is readily available. This is a broad analysis of all fires occurring at all times of the day and is not an estimate of the waking effectiveness of smoke alarm systems although occupants may have been awakened by the alarms during some of the incidents.

Table 4 provides data from all dwelling fires and identifies the performance of smoke alarms. For the period 2010 to 2018 there were a total of 130,387 incidents where smoke alarms (battery or mains powered) operated and of these incidents an alarm was not raised by an alarm in 28,511 incidents (22%). The reasons why an alarm was not raised by an activated smoke alarm are also reported in the UK statistics and are summarised in Table 5.

Table 4 Operation of Smoke Alarms from all Fires in Dwellings

Year	Total	Present, operated and raised the alarm	Present, operated but did not raise the alarm	Present, but did not operate	Absent
2010/11	36602	13010	3740	6648	13204
2011/12	35403	12804	3800	6763	12036
2012/13	33295	12847	3584	6554	10310
2013/14	31908	12231	3482	6409	9786
2014/15	31331	12562	3327	6182	9260
2015/16	31371	12747	3612	6194	8818
2016/17	30343	12594	3474	6154	8121
2017/18	30744	13081	3492	6364	7807
Total	260997	101876	28511	51268	79342

Based on this data, in 22% of incidents where an alarm operated, it did not alert the occupants. However as shown in Table 5 in a large proportion of these cases the alarm was raised before the detector activated, or no person was in earshot or the outcome was unknown.

It is therefore necessary to adjust the 22% of incidents where an alarm was not raised to estimate the efficacy of smoke alarms as detailed below:

- The other / unspecified category will be distributed proportionately.
- No person in earshot is a function of the design layout but may also include times when a building is unoccupied. For the estimate of efficacy, it will be assumed that full coverage of the smoke alarm system is provided. This category will therefore be distributed proportionately.

- The design objective is to alert occupants, but the “no other person responded” category will be added to the occupants did not respond category when estimating the efficacy, tending to yield conservative results.

These initial reallocations are shown in the bottom row of Table 5.

For the category “Alarm raised before system operated” it is expected that in a large proportion of these incidents the occupants would have been alerted by an alarm if a cue from the fire had not been received before activation since the occupants demonstrated their responsiveness to cues. The data from Duncan [6] was applied and it was assumed that in 85% of the incidents the occupants would have subsequently responded to the alarm and in 15% they would not. This is expected to yield a conservative estimate since all the occupants were sleeping in the Duncan study.

Table 5 Smoke Alarms that Activated but did not Raise an Alarm

Year	Alarm raised before system operated	Occupants did not respond	No other person responded	No person in earshot	Other / Unspecified
2010/11	56.00%	14.00%	1.00%	20.00%	8.00%
2011/12	57.00%	13.00%	1.00%	21.00%	7.00%
2012/13	59.00%	13.00%	1.00%	19.00%	7.00%
2013/14	60.00%	13.00%	1.00%	19.00%	7.00%
2014/15	59.00%	13.00%	1.00%	20.00%	7.00%
2015/16	60.00%	13.00%	1.00%	19.00%	7.00%
2016/17	59.00%	13.00%	1.00%	19.00%	7.00%
2017/18	59.00%	13.00%	1.00%	19.00%	8.00%
Selected Value	59.00%	13.00%	1.00%	19.00%	8.00%
Initial Reallocation	80.8%	19.2%	Nil-reallocated	Nil-reallocated	Nil-reallocated

Note: The “no other person responded” has been conservatively assumed to refer to incidents where a person external to the unit could have heard the alarm but did not respond.

Therefore, it will be assumed that in 19.2% + 80.8% x 0.15 = 31.3% of incidents where the alarm was not raised by the smoke alarms, it was due to inefficacy of the alarm system.

Thus the estimated inefficacy of the alarm system can be calculated to be approximately 22% x 0.313 ≈ 7%.

The estimated efficacy of the smoke alarms is therefore expected to be approximately 93% based on the selected definition.

The statistics on which these estimates have been based would have included incidents where human factors including blood alcohol concentrations, the impact of psychotropic drugs, age etc. would have a significant impact. Further information on these human factors can be found in various publications including, Bruck et al[4], Xiong et al [5].

A.1.1.2 Estimate of Reliability for Mains Powered Smoke Alarms

Table 6 provides a breakdown of the reasons for the failure of mains powered smoke alarms to operate. The outcomes between 2010 and 2018 were consistent with minor trends evident with some data and therefore the base values for analysis were taken as the 2017/2018 values.

Table 6 Percentage of Mains Powered Smoke Alarms that did not Operate in Primary Dwellings by Reason for Failure (based on Home Office Statistics[10])

Year	Missing Battery	Defective battery	Other act preventing alarm from operating	Fire products did not reach detector(s)	Fire in area not covered by system	Faulty system / incorrectly installed	Other
2010/11	1%	0%	14%	46%	12%	8%	19%
2011/12	1%	0%	12%	48%	12%	7%	20%
2012/13	1%	0%	11%	50%	10%	8%	20%
2013/14	1%	1%	10%	48%	13%	7%	20%
2014/15	1%	1%	10%	48%	14%	7%	21%

Year	Missing Battery	Defective battery	Other act preventing alarm from operating	Fire products did not reach detector(s)	Fire in area not covered by system	Faulty system / incorrectly installed	Other
2015/16	1%	0%	10%	47%	14%	6%	22%
2016/17	0%	0%	8%	50%	13%	5%	23%
2017/18	1%	1%	8%	51%	13%	5%	22%
Base Value	1%	1%	8%	51%	13%	5%	22%
Reallocation	1%	1%	10%	65%	17%	6%	reallocated

The “other” category included unknown outcomes and similar data and therefore the entries were proportionately reallocated to the remaining categories as shown in the reallocation row.

“Fire products did not reach detectors” and “fires not covered by the system” are not considered as failure under the definition of reliability (i.e. it is not a design objective to activate if the products of combustion do not reach the detector because the fire is too small or in a distant location).

Therefore, the percentage of “failures” where the detectors did not operate but could be expected to have operated was approximately 18% and this value will be used in the estimate of reliability.

The overall failure rates from fires where smoke alarms were present, which includes fire products not reaching the alarm and fires in areas not covered by the system, is summarised in Table 7 yielding a failure rate of 21%.

The 21% failure rate was then reduced by excluding categories for fire products not reaching the alarm and fires in areas not covered by the system yielding a failure rate of approximately 4% or a reliability of 96% (0.96).

Table 7 Mains Powered Smoke Alarm Failures in Dwelling Fires by Type of Alarm (based on Home Office Statistics[10])

Year	Total	Failed to operate	Failure rate (%)
2010/11	12608	2578	20%
2011/12	12810	2630	21%
2012/13	13240	2717	21%
2013/14	12892	2793	22%
2014/15	13300	2732	21%
2015/16	13818	2906	21%
2016/17	13804	2939	21%
2017/18	14332	3129	22%
Total	106804	22424	21%
Proportion alarm expected activated but did not	N/A	N/A	18%
Smoke alarm failure rate	N/A	N/A	4%

A.1.1.3 Estimate of Reliability for Battery Powered Smoke Alarms

The UK fire statistics obtained from the Home Office web site[10] provide a breakdown of the reasons for the failure of battery powered smoke alarms to operate. The outcomes between 2010 and 2018 were consistent with minor trends evident with some data and therefore the base values for analysis were taken as the 2017/2018 values.

Table 8 Percentage of Mains Powered Smoke Alarms that did not Operate in Primary Dwellings by Reason for Failure (based on Home Office Statistics[10])

Year	Missing Battery	Defective battery	Other act preventing alarm from	Fire products did not reach detector(s)	Fire in area not covered by system	Faulty system / incorrectly installed	Other
2010/11	20%	9%	2%	42%	10%	4%	14%

Year	Missing Battery	Defective battery	Other act preventing alarm from	Fire products did not reach detector(s)	Fire in area not covered by system	Faulty system / incorrectly installed	Other
2011/12	19%	10%	2%	42%	11%	3%	13%
2012/13	18%	9%	2%	45%	10%	3%	12%
2013/14	14%	8%	2%	44%	13%	3%	15%
2014/15	15%	10%	2%	44%	12%	3%	15%
2015/16	14%	9%	2%	43%	12%	3%	17%
2016/17	12%	10%	3%	44%	12%	3%	17%
2017/18	12%	10%	2%	45%	12%	3%	17%
Base Value	12%	10%	2%	45%	12%	3%	17%
Reallocation	14%	12%	2%	54%	14%	4%	Nil - reallocated

The other category included unknown outcomes and similar data and therefore the entries were proportionately reallocated to the remaining categories as shown in the reallocation row.

"Fire products did not reach detectors" and "fires not covered by the system" are not considered as failure under the definition of reliability (i.e. it is not a design objective to activate if the products of combustion do not reach the detector because the fire is too small or in a distant location).

Therefore, the percentage of "failures" where the detectors did not operate but could be expected to have operated was approximately 32% and this value will be used in the estimate of reliability.

The overall failure rates from fires where smoke alarms were present, which includes fire products not reaching the alarm and fires in areas not covered by the system, is summarised in Table 9 yielding a failure rate of 39%.

The 39% failure rate was then reduced by excluding categories for fire products not reaching the alarm and fires in areas not covered by the system yielding a failure rate of 13% or a reliability of 87% (0.87).

Table 9 Battery Powered Smoke Alarm Failures in Dwelling Fires by Type of Alarm (based on Home Office Statistics [7])

Year	Total	Failed to operate	Failure rate (%)
2010/11	10790	4112	38%
2011/12	10574	4170	39%
2012/13	9773	3877	40%
2013/14	9219	3643	40%
2014/15	8739	3497	40%
2015/16	8687	3328	38%
2016/17	8421	3259	39%
2017/18	8514	3265	38%
Total	74717	29151	39%
Proportion alarm expected activated	N/A	N/A	33%
Smoke alarm failure rate	N/A	N/A	13%

A.1.2 US Data

A.1.2.1 Analysis of Data from Smoke Alarms in US Home Ahrens[11]

The NFPA publication Smoke Alarms in US Home Fires is published periodically and presents an analysis of fire incident data and a summary of information from other sources. The latest edition was published in 2015 (Ahrens [11]) and covers the 2009-2013 time period.

A direct indication of reliability can be obtained from the statistics for smoke alarm operation in home fires large enough to activate alarm by power source on which the following has been based:

- Battery operated alarms – 80% operated
- Hard wired with battery backup – 95% operated.

The reasons for failure of the smoke alarms to operate when the fire was considered large enough to activate the alarm are provided in Table 10.

Table 10 Reason Smoke Alarms Did Not Operate in Home Structure Fires Considered Large Enough to Activate: 2009-2013 from Ahrens [11]

Type	Missing or disconnected Battery	Dead or Discharged	Lack of cleaning	Hardwired power failure, shut-off or disconnect	Defective unit	Improper Installation or placement	Unclassified
Battery	54%	31%	4%	N/A	3%	3%	5%
Hard wired with battery backup	25%	5%	10%	23%	10%	5%	23%

Ahrens also reported the effectiveness of operating smoke alarms in Home Structure fires which is more closely related to the definition of efficacy adopted for the Group C Data Sheets.

Table 11 Effectiveness of Operating Smoke Alarms (Ahrens [11]

Description	Number of Fires
Alerted occupants and occupants responded	153,900
Alerted occupants but occupants failed to respond	8,600
No occupants	22,200
Failed to alert occupants	4,700
Total	189,400
Total occupied dwellings	167,200

The probability of occupants not being alerted is therefore:

4700/167200 = 0.028

and the probability of occupants not being alerted or not responding is:

(4700+ 8600) / 167200 =0.0795.

Based on the definition of efficacy applied to smoke alarms the efficacy – "Smoke alarms alert occupant if the smoke alarms operate" the efficacy estimated from the US data would be 97%.

Alternatively, efficacy can be defined based on the reduction in fatality rates as detailed below.

The death rate / 100 reported home structure fires by smoke alarm status results indicate:

- 5.3 fatalities / 1000 fires if a smoke alarm is present and operates
- 11.8 fatalities / 1000 fires if there was no smoke alarm present or it did not operate
- 18.9 fatalities / 1000 fires if a smoke alarm is present but did not operate.

This indicates a reduction in fatalities / 1000 fires of approximately 55% if alarms are present and activated compared to buildings without an alarm system or it did not operate. This provides an alternative means of defining and expressing the efficacy of smoke alarms.

The NFPA study also referred to UK statistics indicating a reduction from 8 fatalities / 1000 fires with no smoke alarms operating to 4 fatalities / 1000 fires with smoke alarms that operated within 5 minutes of ignition yielding a reduction of 50%.

If efficacy was based on the reduction in fatality rates a value of between 50 and 55% would be expected based on the above data. This is substantially less than the estimate of approximately 97% based on smoke alarms alerting occupants if the smoke alarms operates highlighting the importance of clearly stating the definition of efficacy when quoting the efficacy of a system.

A.1.2.2 NFPA 72 Estimates of Reliability

Clause A 29.6.3 of NFPA 72:2019 [9] includes the following assumptions with respect to the reliability of fire alarm systems:

"(2) Reliability of fire alarm systems. Fire alarm systems located in dwelling units and having all of the following features are considered to have a functional reliability of 95 percent:

(a) Utilizes a control unit

(b) Has at least two independent sources of operating power

(c) Monitors all initiating and notification circuits for integrity

(d) Transmits alarm signals to a constantly attended, remote monitoring location

(e) Is tested regularly by the homeowner and at least every 3 years by a qualified service technician

(3) Reliability of fire alarm systems without remote monitoring or with wireless transmission. Fire alarm systems for dwelling units with all of the preceding features except (d) or systems that use low-power wireless transmission from initiating devices within the dwelling units are considered to have a functional reliability of 90 percent.

(4) Reliability of other systems. Fire alarm systems for dwelling units comprised of interconnected smoke alarms where the interconnecting means is monitored for integrity are considered to have a functional reliability of 88 percent. If the interconnecting means is not supervised or the alarms are not interconnected, such systems are considered to have a functional reliability of 85 percent."

Sub Clauses (2) and (3) applies to applications where smoke alarms within SOUs are integrated into a general detection and alarm system for a large apartment building, for example, with assumed reliabilities varying from 90 to 95% depending on the type of system adopted.

Sub Clause (4) relates to mains powered smoke alarm systems with battery backup as required within SOUs by the NCC with an assumed *reliability of 85-88%. These estimates are substantially below the values of 95% and 96% derived from recent fire statistics.”*

A.1.3 New Zealand Housing Condition Survey

A housing condition survey of 494 properties was undertaken in 2010 and reported in BRANZ Study Reports SR 240[12] and SR 264[13] with supplementary data provided in SR291 [14]. Approximately 94% of owner-occupied houses and 89% of rented houses contained smoke alarms. Mains powered smoke alarms were present in 8% of houses with battery operated alarms in the remainder.

Approximately 7% of rental houses and 9% of owner-occupied houses with smoke alarms contained at least one smoke alarm that was not operational. Based on these results a reliability with an upper bound of approximately 92% would be expected from a sample of predominantly battery-operated smoke alarms.

A.1.4 Summary of Outcomes from Data Analysis

Table 12 Summary of Outcomes from Data Analysis (some detection systems)

Source	Reliability	Efficacy	Effectiveness
UK Statistics (Mains powered)	96%	93%	89%
UK Statistics (Battery powered)	87%	93%	81%
NFPA Ahrens 2015 [11] Mains	95%	97%	92%
NFPA Ahrens 2015 [11] Battery	80%	97%	78%
NFPA Assumptions	85-88%	N/A	N/A
NZ Housing Survey majority > 90% battery- operated	<92%	N/A	N/A

A.2 Background to Smoke Detection System Estimates

A.2.1 B.1 Review of Data and Analysis - Marsh Study for New Zealand Fire Service Commission

A detailed generic component-based study supported by system-based data for simple and complex smoke detection systems was undertaken by Marsh Ltd. for the New Zealand Fire Service Commission[15] based on a review of international data and information from surveys undertaken in New Zealand.

Fault trees were constructed and the basis of the estimates is documented in the Marsh report [15]. Operational reliability and availability were considered separately by Marsh whereas a generally reliability value, which combines the operational reliability and availability, has been adopted in the Group C Data Sheets.

Availability takes into account the periods for which a system is not operational (or available). Typical examples include:

- isolation during building work (to avoid false alarms)
- isolation during repair, testing and maintenance activities.

Where appropriate the Marsh report identified, low, high and most likely (typical) values for various inputs and used these values to calculate the likely range and most likely values for reliability (operational reliability and availability).

The results are summarised in Table 13 for a simple and complex analogue addressable system with photoelectric smoke detectors.

The approach adopted is likely to overstate the reliability range for the detection systems based on the fault tree analysis because all the low inputs were used to calculate the low reliability estimate and all the high values for the high estimate.

Table 13 Reliability of Analogue Addressable Systems Calculated from March Report[15] Availability and Operational Reliability Estimates

Occupancy	Complexity	Low	Most Likely	High
Apartment	Simple	90.6%	98.0%	99.2%
Apartment	Complex	67.9%	87.9%	99.2%
Office	Simple	90.4%	97.9%	99.2%
Office	Complex	67.7%	87.9%	99.2%

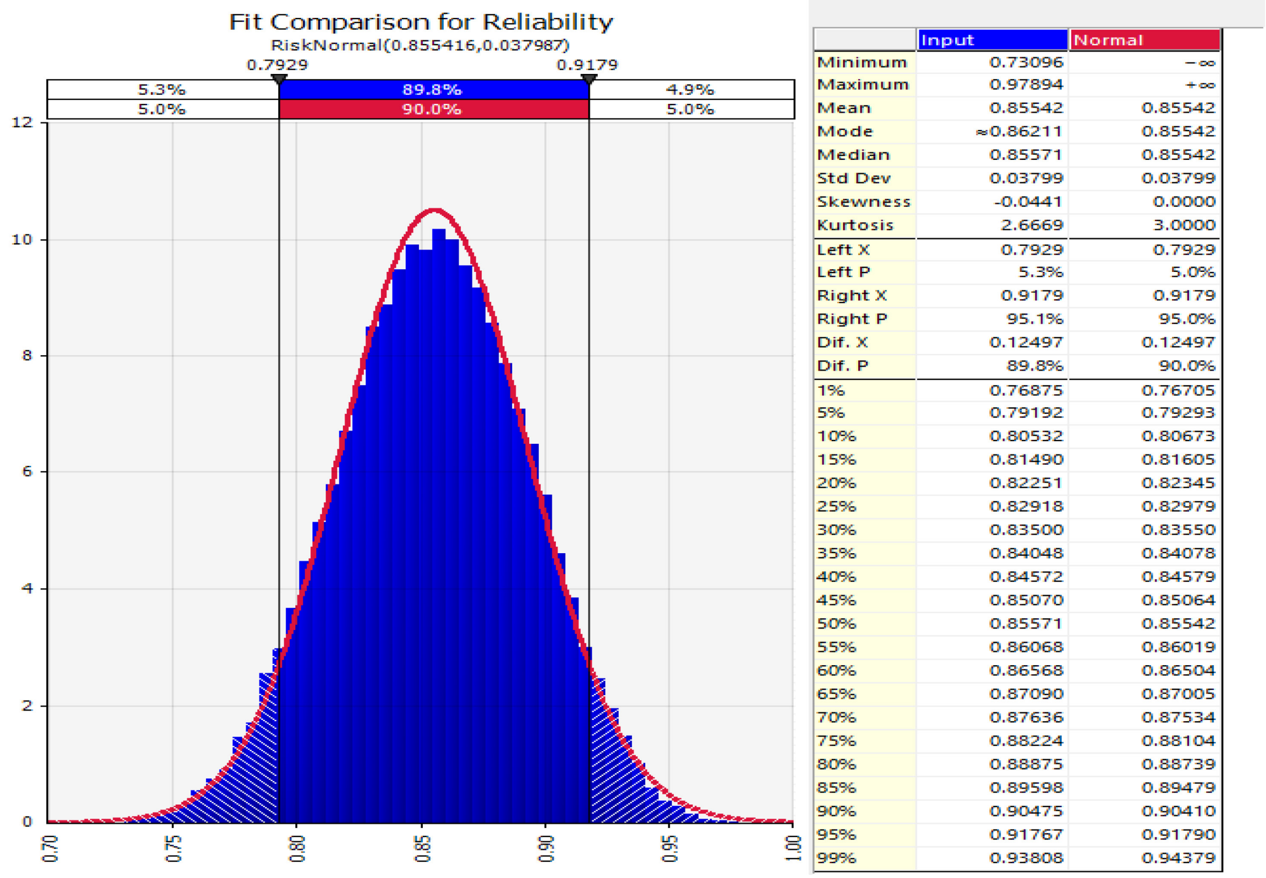
An alternative approach is to define a triangular distribution for the inputs with the base spanning between the lowest and highest values and the apex corresponding to the most likely value and undertake a multi-scenario analysis to derive a distribution for the reliability. This has been undertaken and the resulting distribution approximates to a normal distribution.

Table 14 Reliability of Analogue Addressable Systems Calculated Based on March Report[15] Fault Tree Inputs but Using a Multi-scenario Analysis

Occupancy	Complexity	Low (5-percentile)	Mean	High 95-percentile	Standard Deviation
Apartment	Simple	94.3%	96.0%	97.7%	1.06%
Apartment	Complex	79.4%	85.6%	91.9%	3.8%
Office	Simple	94.2%	95.9%	97.7%	1.06%
Office	Complex	79.3%	85.5%	91.8%	3.8%

The typical output for the office building with a complex system is shown in Figure 10 Multi-scenario Results for Office with a Complex Analogue Addressable Smoke Detection System Using Inputs from Marsh[15] with a normal distribution fitted over the multi-scenario results. The main cause of the large variation between simple and complex systems was the probability of programming errors and the differences between the office and apartment buildings was due to the assumed probability of the unavailability of the system.

Figure 4 Multi-scenario Results for Office with a Complex Analogue Addressable Smoke Detection System Using Inputs from Marsh[15]



	Input	Normal
Minimum	0.73096	−∞
Maximum	0.97894	+∞
Mean	0.85542	0.85542
Mode	≈0.86211	0.85542
Median	0.85571	0.85542
Std Dev	0.03799	0.03799
Skewness	-0.0441	0.0000
Kurtosis	2.6669	3.0000
Left X	0.7929	0.7929
Left P	5.3%	5.0%
Right X	0.9179	0.9179
Right P	95.1%	95.0%
Dif. X	0.12497	0.12497
Dif. P	89.8%	90.0%
1%	0.76875	0.76705
5%	0.79192	0.79293
10%	0.80532	0.80673
15%	0.81490	0.81605
20%	0.82251	0.82345
25%	0.82918	0.82979
30%	0.83500	0.83550
35%	0.84048	0.84078
40%	0.84572	0.84579
45%	0.85070	0.85064
50%	0.85571	0.85542
55%	0.86068	0.86019
60%	0.86568	0.86504
65%	0.87090	0.87005
70%	0.87636	0.87534
75%	0.88224	0.88104
80%	0.88875	0.88739
85%	0.89598	0.89479
90%	0.90475	0.90410
95%	0.91767	0.91790
99%	0.93808	0.94379

A.2.2 Bukowski Study 1999

Bukowski et al [16] undertook a detailed review to provide estimates of the operational reliability of fire protection systems based on previous studies and data available at the time - 1999. This data will reflect older systems (conventional) and its unqualified application to modern systems could be questionable.

Table 15 Reliability Estimates for Smoke Detection Systems from Bukowski et al [16]

Occupancy	Low (5-percentile)	Mean	High 95-percentile
Residential	75.1	77.8	80.6
Institutional	82.3	83.5	84.6
Commercial	70.2	72	73.7

A.2.3 Other Estimates of Reliability

Zhang et al [17] listed the following default reliability values for use in CU Risk if no more appropriate data is available. CU Risk is a QRA model developed by Carleton University.

Table 16 Default Failure Probabilities from Zhang et al[17]

Device type	Reliability
Local alarm	0.75
Sprinklers	0.85
Smoke detectors	0.9
Heat detectors	0.9
Central alarm	0.9
Voice alarm	0.9

Moinuddin and Thomas[18] estimated that the reliability of smoke detectors was approximately 90% and the failure probabilities at the FIP panel were as indicated in Table 17 which also included data from a VTT Study[19].

Table 17 Failure Probabilities of FIP (Mean Value) from Moinuddin and Thomas[18]

Components	Moinuddin	VTT [19]
FIP panel	0.11	0.06
FIP back up battery / UPS	0.01	0.03
Monitor alarm signal	0.04	0.08

Clause A 29.6.3 of NFPA 72:2019 [9] includes the following assumptions with respect to the reliability of fire alarm systems:

> *"(2) Reliability of fire alarm systems. Fire alarm systems located in dwelling units and having all of the following features are considered to have a functional reliability of 95 percent:*
>
> *(a) Utilizes a control unit*
>
> *(b) Has at least two independent sources of operating power*

(c) Monitors all initiating and notification circuits for integrity

(d) Transmits alarm signals to a constantly attended, remote monitoring location

(e) Is tested regularly by the homeowner and at least every 3 years by a qualified service technician.

The above features are consistent with a residential building using a general fire detection system.

British Standard PD 7974:2003[20] suggests *"the reliability of alarm box, wiring and sounders is in the range 0.95 to 1 and the reliability of commercial smoke and heat detectors is 0.9. Therefore, the probability of successful operation would be in the range 0.85 and 0.9."*

A.3 Appendix C References

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Data Sheet C4 Effectiveness of Active Smoke Control Systems

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet C4 addresses, Active Smoke Control System Effectiveness and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1 General overview of the effectiveness of fire protection systems
- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C3 Detector Effectiveness
- Data Sheet C5 Smoke Barrier Effectiveness
- Data Sheet C6 Fire Barrier Effectiveness

- Data Sheet C7 Smoke and Fire door Effectiveness
- Data Sheet C8 General Methods for Conversion of Fire Resistance Times.

Data Sheet C4 Contents

Version	Date	Data Sheet	Comments
C4-1	Jan 2019	C4	Initial draft for comment
C4-2	Jun 2019	C4	Draft for publication

1.1 General Definition of Effectiveness

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*

- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

1.2 Types of Active Smoke Control Systems

The following are common types of active smoke control systems. Typical expectations for the design installation commissioning, inspection and testing of active smoke control systems in Australia are included in: AS 1668.1[2], AS 1682.1 [3], AS 1682.2[4] and AS 1670.1 [5], AS 1851 [6] and the NCC[1].

1.2.1 Shutdown Systems (Including Closure of Smoke Dampers.

These requirements generally apply to HVAC systems that recycle air from one *fire compartment* to another or may unduly contribute to the spread of smoke between *fire compartments*.

The objective is to limit smoke spread between *fire compartments* by shutting down the air-handling system and activating the smoke dampers to close automatically upon activation of fire mode. (Note; this is in addition to any requirement to maintain the fire resistance of the wall or floor).

1.2.2 Automatic Air Pressurisation Systems

Automatic air pressurisation systems deliver outdoor air into the required shaft or enclosure to create a pressure differential to prevent the spread of smoke from an adjoining enclosure. There are a number of variants described in the following sub-sections.

1.2.2.1 Fire-Isolated Exit Pressurisation Systems

Automatic air pressurisation systems are used for protection of fire-isolated *exits* where appropriate. The NCC DTS provisions reference AS 1668.1 which, amongst other things, requires an airflow of not less than 1 m/s to be maintained through each open doorway to the fire affected compartment when all doors to the fire affected compartment are open together with the main discharge doors from all fire-isolated *exits*.

The objective is to pressurise fire-isolated *exits* such that smoke will not infiltrate the *exit* even when a prescribed number of doors are open which requires significant air flows and consequently provision for air / pressure relief needs to be provided to prevent the development of excessive pressures causing excessive door opening forces or prevention of *automatic* closing functions of doors.

1.2.2.2 Lift Shaft Pressurisation Systems

The lift shaft (or group of shafts) is pressurized with outdoor air to create a pressure difference between the shaft and all other compartments. Further details are provided in AS 1668.1.

The objective is to restrict the spread of smoke from a fire-affected compartment to a non-fire-affected compartment via the lift shafts.

1.2.3 Zone Pressurization Systems

Zone pressurization systems are used to minimise the risk of fire and smoke spread from the fire zone to adjacent zones by generating a pressure differential. The DTS provisions reference AS 1668.1.

The objective is to generate a pressure differential between the zones such that smoke spread through any small openings will not occur. This is generally achieved by:

- exhausting smoke from the fire affected compartment directly to atmosphere
- controlling return air relief from non-fire affected compartments and supplying uncontaminated air to all non-fire affected compartments to maintain a positive pressure relative to the fire affected compartment
- pressurisation of fire-isolated *exits*.

1.2.4 Automatic Smoke Exhaust Systems

Automatic smoke exhaust systems are used to maintain a smoke free area to facilitate the evacuation of occupants and *fire brigade* intervention at a lower level by extracting smoke from the hot layer at or close to the roof or ceiling level using a forced extraction system. The supply of sufficient make-up air at a low level is critical and provisions for make-up air must be considered as an integral part of the smoke exhaust system. The DTS provisions are stated in Specification E2.2b of the NCC. The objective is to maintain the tenability within the enclosure and escape routes for sufficient time for evacuation of the occupants and facilitate *fire brigade* intervention.

1.2.5 Automatic Smoke-and-Heat Vents

Automatic smoke-and-heat vents operate on similar principles to powered smoke exhaust systems except that smoke-and-heat vents rely on the buoyancy of hot gases to generate the necessary air flows. It is necessary to provide sufficient make-up air at floor level and provisions for make-up air must be considered as an integral part of the smoke-and-heat vent system. The DTS provisions are stated in Specification E2.2c of the NCC. The objective is to maintain the tenability within the enclosure and escape routes for sufficient time for evacuation of the occupants and facilitate *fire brigade* intervention.

1.3 Overview of Effectiveness of Smoke Control Systems

1.3.1 Influence of Complexity on Reliability

Active smoke control systems can vary considerably from simple systems having very few components to complex systems and it therefore follows that the reliability of the systems will vary substantially.

For demonstration purposes Klote and Milke[7] made the following simplifying assumptions to provide some generic estimates for systems having varying complexities which are summarised below:

- the smoke control system is a series system whereby failure of any component will cause failure of the entire system (this simplifies calculations since the reliability of a series system is the product of the reliabilities of the components)
- a reliability of 0.99 was assumed for fans and 0.94 for other components
- it is assumed all systems and components are operational at the end of the commissioning process (note; this is considered unlikely based on experience of a range of practitioners and facility managers considered by Fazio [8] when investigating the reliability of stair pressurisation systems)
- failure rates of 10^{-6}/h for fans and 10^{-5}/h for other components were assumed.

Table 2 Estimated System Reliabilities and Mean Life of Commissioned Systems from (Klote and Milke [7]

System	No. of HVAC System Fans	No. of Other Components	Reliability of New System Before Commissioning - %	Mean life of Commissioned System (months)
1	3	0	97	16
2	0	3	83	46
3	3	9	56	14
4	5	18	31	8
5	5	54	3	3

It therefore follows that the reliability of a system could be improved by:

- minimising the number of components in the system without compromising performance
- avoiding the use of complex components
- maximizing the number of components that are operated regularly in normal mode
- including monitoring devices to remotely test the operation of key components and alert facility managers of faults.

1.3.2 Installation, Commissioning and Maintenance

It is unlikely that all systems will be fully operational at the end of commissioning in all cases and to approach this goal a program of acceptance inspection and testing and defect correction is necessary during commissioning. Such commissioning should include the following processes and the processes of repair and retesting may need to be repeated several times:

- an installation check of all components
- tests of system performance during all modes of operation
- repair of defects
- retesting until all defects are corrected.

Whilst extensive requirements for commissioning and subsequent maintenance are provided in AS 1668.1[2] and AS 1851 [6] this may not always be fully implemented. This was also noted by Klote and Milke from a US perspective where they observed that “Current construction practices are such that system commissioning is not always this exhaustive”.

General estimates of probabilities of installation faults and the probability of installation faults not being corrected during the commissioning process were summarised in a report on the Effectiveness of Fire Safety Systems for Use in Quantitative Risk Assessments for the New Zealand Fire Service Commission (Marsh report) [9] which referenced earlier work by the Fire Code Reform Centre by

Zhao [10] and Fazio [8] in Australia but made adjustments to reflect NZ installation and commissioning practices and are reproduced in Table 3.

Table 3 Combined Probability of a Fault following Commissioning based on Marsh Report[9]

Installation and Commissioning Quality	Probability of Fault Post Commissioning	Reliability Post Commissioning %
High	0.01	99
Medium (typical)	0.1	90
Low	0.3	70

Note: The reliabilities in Table 3 do not consider the complexity of a system.

From the estimate of the mean life of a commissioned system in Table 2, regular maintenance or routine servicing is critical to the achievement of a reasonable level of reliability through the life of a system irrespective of the quality of the installation and commissioning processes. The maintenance / servicing should include comprehensive inspection and testing of systems. To facilitate this, it is critical that safe and easy access is available to inspect, test and service equipment and specifications are provided and implemented for regular testing, inspection and maintenance of a system which may be based on AS 1851 [6], adjusted as appropriate for the specific system.

1.4 Interactions with Other Systems and Common Mode Failures

1.4.1 Failure of the Fire Detection System

The fire detection system can form an integral part in many active smoke control systems particularly for more complex systems where it is not only critical to signal activation of the fire alarm but also to correctly identify the location of the alarm for systems such as zone pressurisation systems. Failure to achieve these outcomes are examples of common mode failures that need to be considered for the FSVM scenarios where it is necessary to consider potential failures of systems. Further information of smoke detection systems is provided in Data Sheet C3.

1.4.2 Interaction with Automatic Fire Sprinkler Systems

Some active smoke control systems depend on a sprinkler system to limit the fire size. Failure of the sprinkler system to operate or limit the fire to the required size could compromise the efficacy of an active smoke control system by overwhelming the capacity for smoke exhaust and / or overheating components leading to degradation of performance or failure. It is therefore necessary when evaluating the consequences of failure of a sprinkler system to also consider the impact of failure of sprinkler systems on smoke control measures. Further information of sprinkler systems is provided in Data Sheet C2.

1.4.3 Door Opening / Closing Forces

Pressurisation systems and general airflows initiated by active smoke control measures can compromise the correct functioning of a door assembly by:

- exceeding permitted opening forces for *exit* doors
- preventing *automatic* closure of fire and smoke doors.

There are practical limits to air flows and pressure differentials that will compromise the operation of a door assembly. These depend on the door dimensions, amongst other things.

1.5 Categorising Active Smoke Control System Effectiveness

The following definitions have been selected in relation to active smoke control system effectiveness, but it is noted that depending upon the matters under consideration it is valid to adopt alternate definitions provided the effectiveness estimates are modified accordingly.

Efficacy

For the purposes of the Group C Data Sheets efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification.

The criteria for efficacy for active smoke control systems depend on the type of system, amongst other things and typical examples are provided in Section 1.2.

In many cases the achievement of these objectives is dependent on the performance of other fire protection systems and building configurations. Therefore, efficacy will generally need to be estimated on a case by case basis, based on smoke modelling undertaken as part of the fire engineering analysis and taking account of safety factors adopted for deterministic analysis or assumed distributions of variables if a probabilistic analysis is undertaken.

Active Fire Protection System Reliability varies substantially depending upon the complexity of the system and quality of installation, commissioning and maintenance.

Reminder

Note: Fault tree analysis can be used to better understand the importance of various components of the system subject to relevant component fault data being available. Such an approach can be used to determine how to improve system reliability.

Generic estimates based predominately on component studies and field surveys are provided in Section 1.6. The basis for the estimates is summarised in Appendix A.1 to allow users to determine if they are appropriate for the specific circumstances or a more detailed component analysis for a specific design is required.

Effectiveness is taken as the product of the Efficacy and Reliability expressed as a %.

1.6 Estimates of Active Smoke Control System Effectiveness

There is limited data and substantial variability in values for the reliability of active smoke control systems and this generally reflects variations in complexity / number of critical components and details of the design which may impact on the robustness of the system and sensitivity to the quality of installation, commissioning and maintenance.

Appropriate skill and diligence are expected to be employed throughout the design, installation, commissioning, and maintenance of the system, throughout the life of the building. These requirements should be reflected in the fire safety strategy and fire safety handbook developed for the project and relevant design documentation.

If there is no more appropriate data for a specific application the generic values provided in Table 3 should be considered and a sensitivity analysis undertaken using the high and low values subject to confirmation from the PBDB stakeholders. Further information on the data and published literature used as the basis for the estimated values is provided in Appendix A.1.

Table 4 Typical Design Value for Australian Systems

Type of Active Smoke Control System	Reliability: Typical	Reliability: Low	Reliability: High
Shutdown	75%	65%	80%
Fire-Isolated *Exit* Pressurisation	50%	30%	60%
Lift Shaft	70%	60%	75%
Zone Pressurization	30%	15%	50%
Smoke Exhaust	80%	70%	85%
Smoke-and Heat-Vents	80%	70%	85%

The majority of the data referenced in Appendix A.1 predates the current versions of the relevant design and servicing standards that incorporate requirements for design, commissioning, inspection, testing and include significant content that may enhance the reliability of active smoke control systems if fully implemented.

Also, there have been substantial changes to many components such as damper motors, variable speed drives (VSDs), etc, that incorporate newer and generally more intelligent and efficient technology. Therefore, the historical perceptions / data may not always be entirely accurate for newer systems.

A detailed fault tree analysis can be undertaken to derive the reliability of a current system for a project to take account of the specific design features. It is, however, important to fully develop the fault trees to reduce the risk of failure modes not being identified and consider human factors relating to design commissioning and maintaining in-service performance.

The efficacy of the various systems will vary based on the *fire hazard* and features of a building and generally will need to be derived on a case by case basis. However the estimates of reliability for fire-isolated *exit* pressurisation in Table 34 were based to a large extent on the work of Fazio [8] which took account of a number of variables that impact on the efficacy and therefore the generic effectiveness of the fire-isolated *exit* pressurisation system may be assumed to approximate to the stated reliability in Table 4.

Systems such as smoke-and-heat vents are sensitive to external environmental effects, the maximum fire size and the natural buoyancy of smoke and therefore the efficacy of these systems may be relatively low.

The FSVM uses a comparative approach rather than an absolute approach which can reduce the sensitivity of the results to estimates of effectiveness. For example, if the same active smoke control system forms part of the fire safety strategy for the *reference building* and proposed *Performance Solution* the outcomes are expected to be less sensitive than a fire safety strategy where a proposed *Performance Solution* considers variations to the active smoke control system. In these instances, the generic values may be used but the expected variation to the reliability could be estimated based on a fault tree analysis focussing on specific variations.

A.1 C4 Appendix A Background to Estimates of System Effectiveness

Since efficacy is to be estimated on a case by case basis generic reliability values will be estimated in this section only.

Fazio et al [11] provided estimates based on undertaking large numbers of audits on Australian buildings and indicated that the values obtained are most likely to reflect high levels of maintenance (above average) because the owners / property managers have voluntarily commissioned an external body to undertake the audits in most cases. Whilst individual results were not analysed, and reliance was placed on the judgement of the auditors, the indicated values provide very useful system-level assessments.

Another finding from this study critical to reliability estimates is that faults may be recorded in maintenance logs, but the property / facility manager is not made aware of the faults unless an audit of the records is undertaken. Typically, at best this would be annually. This extends time estimates for rectification of faults and consequently reduces reliability.

A.1.1 Shutdown Systems (Including Closure of Smoke Dampers)

Fazio et al [11] estimated that on alarm, air handling units (AHUs) shut down when they were supposed to, in 90% of audits of Australian office and retail buildings and the AHUs return air dampers closed in 84% and 86% of audits of office and retail buildings, respectively.

The overall reliability of a typical system will therefore be assumed to be approximately 75% with the efficacy depending upon fire modelling outcomes.

In some cases it may be more appropriate to consider *automatic* shut down and closure of air dampers separately particularly if variations to smoke control systems are being evaluated.

A.1.2 Fire-Isolated Exit Pressurisation Systems

Zhao[10] estimated the reliability for a stair pressurisation to be 90% assuming a signal activation of the fire alarm was received and recognised. The analysis did not determine the probability of the required air flows and door opening forces amongst other things, being achieved and therefore would be expected to provide an over estimate of reliability.

Fazio et al [11] estimated that stair pressurisation system fans failed to start on alarm in 10% of audits of Australian offices and 8% of Australian retail premises. This value addresses one mode of failure of stair pressurisation systems and is consistent with the simplified analysis and criteria adopted by Zhao[10].

Fazio[8] undertook a detailed component analysis with failure probabilities based on surveys of Australian industry practitioners involved in the design, installation, commissioning and maintenance of fire-isolated *exit* pressurisation systems. Two example buildings were considered in detail. The stair pressurisation systems had been installed for many years enabling the actual designs to be considered and maintenance records examined. Fazio indicated that by adopting criteria such as air velocities and door opening forces for reliability the estimates obtained could be considered to inherently address the efficacy component of effectiveness and therefore the fault tree estimates can be used to derive the effectiveness of the systems directly.

When assessed against all the performance criteria of AS 1668.1 very low reliabilities were obtained for both the systems analysed (less than 10%). These criteria include limits to sound levels which whilst an important health and safety consideration with potential to impact on the evacuation efficiency do not directly relate to the effectiveness of a smoke control functions.

It is possible to focus on the critical parameters of door forces and air flows by selecting top events of the fault tree as door forces greater than 110N or air velocities less than 1 m/s. On this basis:

- the effectiveness with respect to airflow was estimated to be 36% (using mean of all component estimates) and 49% (ignoring extreme estimates) for the first system and 63% (using mean of all component estimates) and 30% (ignoring extreme estimates) for the second system
- the effectiveness with respect to door opening forces was estimated to be 8% for System 1 and 10% for System 2.

It should be noted that smoke spread to the stair may be adequately retarded during some scenarios at velocities below 1 m/s and depending upon occupant capabilities doors may be able to be opened despite opening forces greater than 110N.

Fazio indicated that the reason for the high probabilities of component failure (and therefore, low effectiveness values) could be attributed to either one, or combination of, the following:

- the system may not have been commissioned
- the system may not have been maintained previously (i.e. only now has a maintenance program been developed for the system)
- the faulty item(s) identified may not be fixed prior to the next maintenance inspection, if ever.

Moinuddin and Thomas [12] reviewed maintenance records from 10 buildings (considered to reflect buildings with high levels of maintenance / inspection) and estimated the failure probabilities of velocity through doors and door opening forces are both below 20%, although details of the assumptions made in the estimates and extent of verification of airflow data are not provided.

Lay [13] estimated that 35% of pressurisation systems might fail to function as intended based on the experience of a range of fire safety professionals, product suppliers, building occupiers and researchers.

The Marsh Report [9] also included estimates of the reliability of stair pressurisation systems based on the previous studies by Zhao and Fazio with modifications to take into account New Zealand practices and provided the following estimates ignoring construction aspects such as stairwell tightness and door hardware to provide values related specifically to the smoke control function.

Table 5 Stairwell Pressurisation System Reliability - Smoke Control Function Only (from Marsh Report [9])

System Description	Expected reliability	Lower reliability	Upper reliability
Fixed speed fan and barometric dampers	60%	28%	84%
Variable speed drive system	47%	14%	80%
Variable speed drive and motorised damper system	52%	16%	82%

Based on the above review a typical generic effectiveness for a stair pressurisation system with respect to maintaining adequate pressure / airflow will be assumed to be 50% for a typical system.

A.1.3 Lift Shaft Pressurisation Systems

The lift shaft (or group of shafts) is pressurised with outdoor air to create a pressure difference between the shaft and all other compartments. Further details are provided in AS 1668.1.

The objective is to restrict the spread of smoke from a fire-affected compartment to a non-fire-affected compartment via the lift shafts.

The operation of this system is expected to be simpler than a stair pressurisation system but more complex than a shut down system and therefore a reliability of approximately 70% for a typical system will be assumed.

A.1.4 Zone Pressurization Systems

Zhao[10] derived the reliability estimates shown in Table 6 for a typical zone pressurization system assuming an alarm was received from the FIP. He also provided estimates for likely and partial reliability recognising that performance criteria may not be satisfied but the system could operate satisfactorily in some scenarios.

Table 6 Estimates of Zone Pressurisation by Zhao

No. of Floors	Complete Reliable	Likely Reliable	At Least Partial Reliable
5	53.4	53.4	73.4
10	34.1	62.9	73.7
20	13.9	61.3	71.8

The above analysis indicates that the reliability of a zone pressurisation system may be substantially below that of a stair pressurisation system which is to be expected because of the added complexity. A typical value for reliability will be therefore taken as 30%.

A.1.5 Automatic Smoke Exhaust Systems

Fazio et al [11] estimated that on alarm, smoke spill (exhaust) fans operated in 94% of audits of Australian offices and 91% of retail buildings.

It will be assumed that a similar reliability applies to the provision of makeup air that is required for the system to operate effectively and therefore a reliability of 80% has been assumed.

A.1.6 Automatic Smoke-and-Heat Vents

Without any further data being available, the same reliability as that proposed for the *automatic* smoke exhaust system will be adopted, i.e. 80%.

A.1.7 Estimating Low Typical and High Values of Reliability.

Estimating low, typical and high values involves a significant level of subjectivity due to the variability of values from available studies and potential variability of the complexity of design, robustness and maintainability of the design in addition to the variability in the quality and supervision relating to installation, commissioning and ongoing maintenance of the systems.

To provide some level of consistency and transparency the typical values were estimated from the above data. A basic level of performance was assumed for each type of system before commissioning taking into account the outcomes of the comparative analysis undertaken by Klote and Milke [7] of systems with different complexity (refer Section 1.3.1).

A probability of a fault remaining, or new faults developing post commissioning and not subsequently being identified during routine inspection, test and servicing was then assumed for high, typical and low-quality levels of commissioning and the reliability estimated post commissioning for each type of system.

The values adopted for the probabilities of faults not being detected or rectified during commissioning were generally within the following ranges depending on assumed quality of commissioning and the estimates were:

- typical level of commissioning – 0.65 to 0.8
- high level of commissioning – 0.5 to 0.55
- low level of commissioning – 0.9 to 0.95.

It was assumed that the same standards would apply through the life of the building and the reliability would remain at a similar level through the building life without a major intervention.

The outcomes for generic systems are summarised in Table 4 in Section 1.6.

It is noted that in the last decade since most of the studies on which these estimates were based were undertaken there have been significant enhancements to AS 1851, AS 1670.1 and AS 1668.1 that if effectively implemented could improve the reliability of active smoke control systems.

Also, there have been substantial changes to many components such as damper motors, VSD's, etc, that incorporate newer and generally more intelligent and efficient technology. Therefore, the historical perceptions/data may not always be entirely accurate for newer systems.

A.2 C4 Appendix B References

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Data Sheet C5 Smoke Barrier System Effectiveness

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet C5 addresses Smoke Barrier Effectiveness, and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1General overview of the effectiveness of fire protection systems
- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C3 Detector Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness
- Data Sheet C6 Fire Barrier Effectiveness
- Data Sheet C7 Smoke and Fire door Effectiveness

Data Sheet C8 General Methods for Conversion of Fire Resistance Times.

Data Sheet C5 Contents

Version	Date	Data Sheet	Comments
C5-1	Jan 2019	C5	Initial draft for comment
C5-2	Jun 2019	C5	Draft for publication.

1.1 General Definition of Effectiveness

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*

- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

These definitions may not be appropriate for some passive fire protection systems and it may be more appropriate to define performance distributions as described in this Data Sheet.

1.2 Types of Smoke Barrier System

1.2.1 Classification of Smoke Barrier Exposure

Smoke barriers can be used as part of a smoke containment strategy to limit smoke spread to adjacent enclosures and / or paths of travel to *exits* for sufficient time to facilitate the safe evacuation of occupants and *fire brigade* intervention.

The performance of smoke barriers can be expressed in terms of leakage rates or effective flow areas when exposed to ambient, medium or high temperatures.

Ambient medium and high temperatures are commonly defined as described below for design and specification purposes:

Ambient temperature - 20±10˚C

Medium temperature - 200±20˚C

High temperature – temperature representative of a *fully developed fire* (generally the standard heating regime or more severe hydrocarbon heating regime prescribed in AS 1530.4 are adopted for testing systems under standardised conditions [2]).

ISO TR 5925-2 [3] provides commentary relating to the applicability of these conditions and use of test data in a smoke containment strategy providing useful information for the development, analysis and specification of *Performance Solutions* involving smoke containment.

1.2.2 Derivation of Criteria from NCC DTS Smoke Barrier Systems

Specification C2.5 of the NCC [1] sets out DTS provisions for smoke-proof walls which as a minimum allow the use of *non-combustible* barriers that may contain safety glass as defined in AS 1288 [4]. This form of construction is unlikely to act as an effective smoke barrier if exposed to high temperatures as defined in Section 1.2.1 and therefore the primary objective of the NCC DTS provisions is interpreted as providing a barrier that is resistant to ambient and medium temperature conditions unless FRLs are also specified for the barrier.

The NCC does not nominate acceptable leakage limits but it is reasonable to assume that the intent is to achieve a level of airtightness that reflects what is likely to be achieved if due diligence is exercised through the design installation phases and the system is maintained through its design life.

Klote and Milke [5] provided estimates of typical leakage areas based on measurements of flow rates in buildings which were converted to leakage areas assuming a dimensionless flow coefficient C of 0.65 (refer Table 2).

A reasonable approximation of volumetric flow rates can then be calculated for varying temperatures and pressure differentials using Equation 1:

$$\dot{V} = CA\left(\frac{2\Delta P}{\rho}\right)^{1/2}$$ **Equation C5.1**

Where

$\dot{V}$ is the volumetric flow rate through the path (m^3/s)

C is the dimensionless flow coefficient; (0.65)

A is the flow area (or leakage area) (m)

Δp is the pressure difference across path (Pa)

ρ is the density of the gas in path (kg/m^3)

Table 2 Typical Leakage Areas of Walls and Floors of Commercial Buildings (adapted from Klote and Milke [5])

Construction Element	Tightness	Area Ratio $A/A_W \times 10^{-4}$
Exterior building walls (including cracks around doors and windows):	Tight	0.5
Exterior building walls (including cracks around doors and windows):	Average	1.7
Exterior building walls (including cracks around doors and windows):	Loose	3.5
Exterior building walls (including cracks around doors and windows):	Very loose	12
Stairwell walls (including construction cracks but not cracks around doors)	Tight	0.14
Stairwell walls (including construction cracks but not cracks around doors)	Average	1.1
Stairwell walls (including construction cracks but not cracks around doors)	Loose	3.5
Elevator shaft walls	Tight	1.8
Elevator shaft walls	Average	8.4
Elevator shaft walls	Loose	8.4
Floors (including construction cracks and gaps around penetrations)	Tight	0.07

Construction Element	Tightness	Area Ratio $A/A_W \times 10^{-4}$
Floors (including construction cracks and gaps around penetrations)	Average	0.52
Floors (including construction cracks and gaps around penetrations)	Loose	1.7

Notes:

1. Flow areas based on C=0.65 when flows measured at ambient temperatures with a pressure differential of 75Pa.
2. A/A_W is the flow area per unit area of the wall or floor.

A reasonable expectation for an NCC DTS smoke proof wall if due diligence is exercised through the design and installation phases and the system is maintained through its design life would be a Leakage Area Ratio of 1.0×10^{-4}, which approximates to the average airtightness for a stairwell, excluding the impact of any doors or service penetrations and dampers.

To account for general service penetrations the Leakage Area Ratio will be increased to 1.5×10^{-4} assuming that the majority of the contribution to the floor leakage values in Table 2 was from service penetrations. Using Equation 1 the volumetric flow rate per m^2 of wall area at 200°C with a pressure differential of 25Pa including the impact of general services would be expected to be approximately $3m^3/h/m^2$.

Based on the above estimates and NCC DTS requirements for smoke doors and smoke dampers which rely on the test procedures of AS 1530.7 [6], a DTS smoke proof wall (excluding the impact of doors and dampers within the wall) would be expected to maintain Leakage Area Ratios not greater than 1.5×10^{-4} when exposed to temperatures increasing linearly to 200°C over a period of 30 minutes and then being exposed to a temperature of 200°C for a further 30 minutes.

If a smoke proof wall is also required to have an FRL for other purposes, it will need to satisfy the requirements of Clause A5.4 of the NCC to demonstrate the required FRL can be achieved. However, under these circumstances, it is generally only required to demonstrate the criteria for *structural adequacy / integrity / insulation* and supplementary criteria if applicable such as the *resistance to the incipient spread of fire* are satisfied when the element is exposed to high temperatures. Unless specifically required as part of the fire safety strategy the smoke leakage criteria only apply whilst the element is subjected to ambient and medium temperatures.

> ***Reminder***
>
> Note: Significantly higher leakage rates can be expected for some types of specimen exposed to high temperatures compared to the medium and ambient temperature performance, even if the fire resistance performance criteria are satisfied. Also at high temperatures additional smoke may also be produced from the specimen. Reference should be made to observations from fire resistance tests, reference tests or technical literature to make an informed judgement of potential increases to the rate of smoke spread under these conditions. The information in this Data Sheet relates to the performance of smoke barriers exposed to ambient and medium temperatures only unless otherwise stated.

1.2.3 Derivation of Criteria from NCC DTS Smoke Doors

Specification C3.4 of the NCC states under General Requirements that-

> ***Specification C3.4***
>
> Smoke doors must be constructed so that smoke will not pass from one side of the doorway to the other and, if they are glazed, there is minimal danger of a person being injured by accidentally walking into them.

In practice there will tend to be some leakage through an element (including solid barriers based on the measurements provided in Table 2). Since the FSVM adopts a comparative approach and NCC Specification 3.4 provides a DTS form of construction for smoke doors, it is considered reasonable for leakage criteria to be estimated by comparison with the DTS construction when using the FSVM.

AS 6905 [7] specifies the following leakage performance for smoke doors:

(a) Single leaf smoke doors—40 m^3/h at medium temperature conditions (25 m^3/h corrected to Standard Reference Conditions), at a pressure differential of 25 Pa after exposure at 200°C for at least 30 min when subjected to a test in accordance with AS 1530.7 [6].

(b) Two leaf smoke doors—65 m^3/h at medium temperature conditions (40 m^3/h corrected to Standard Reference Conditions), at a pressure differential of 25 Pa after exposure at 200°C for at least 30 min when subjected to a test in accordance with AS 1530.7 [6].

The smoke doors are required to be tested opening towards and away from the heated enclosure unless the direction of exposure can be clearly identified in which case the results from testing with the required exposure apply.

The standard notes that:

- incompatible door and seal combinations may result in higher leakage rates when subjected to the AS 1530.7 [6] test
- leakage rates lower than or equal to the above values are achievable and may be specified as part of a *Performance Solution* to satisfy the *Performance Requirements* of the NCC.

Subject to agreement with the PBDB stakeholders, the requirements of AS 6905 may be considered as an appropriate benchmark for the performance of a smoke door that is equivalent to the DTS construction pending quantification of the required performance.

The effectiveness of smoke doors is considered in more detail in Data Sheet C7.

1.2.4 Derivation of Criteria from NCC DTS Smoke Dampers

The required performance of smoke dampers is specified in AS 1682.1 [8] which is referenced by the NCC through the primary reference standard AS 1668.1 [9]. AS 1682.1 requires:

- **Air leakage** - to be not greater than 100 $L/s/m^2$ (360 $m^3/h/m^2$) when tested in accordance with AS 1530.7 with a pressure differential of 300Pa or for dampers less than 0.5m^2 not greater than 50 L/s (180 m^3/h)
- **Operation time -** travel time in either direction not greater than 30 s under all conditions and should be capable of operating the damper against the design airflow.

The reliability of smoke dampers is addressed as part of the Active Smoke Control System in Data Sheet C4.- -

1.3 Overview of Effectiveness of Smoke Barrier Systems

1.3.1 Adaptation of General Definitions of Effectiveness

1.3.1.1 Application of Efficacy to Smoke Barrier Systems

For the purposes of the Group C Data Sheets, efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification. The criteria for efficacy for smoke barrier systems can be expressed, for example, as the probability that the system will retard the spread of smoke through the barrier to maintain tenable conditions in an adjacent enclosure until evacuation is complete and to facilitate *fire brigade* intervention.

In many cases the achievement of this objective is dependent on the performance of other fire protection systems and building configurations. Therefore, efficacy will generally need to be estimated on a case by case basis, based on smoke modelling undertaken as part of the fire engineering analysis and taking account of safety factors adopted for deterministic analysis or assumed distributions of variables if a probabilistic analysis is undertaken.

1.3.1.2 Application of Reliability to Smoke Barrier Systems

The concept of reliability can be relatively easily applied to components such as smoke doors and smoke dampers within a smoke barrier system where failure of an element to close or be closed when required to be in the closed position clearly represents a failure of the system and the probability of full closure and if appropriate latching can be used to define the reliability of the system assuming there are no errors in the manufacture and installation that could cause a major failure of the smoke door or smoke damper. The reliability of these components is dealt with in Data Sheets C7 and C4 respectively.

The application of the concept of reliability to smoke barriers with service penetrations is more complex because the significance of defects will vary from case to case and may not increase smoke leakage through barrier to such an extent that the design objective is not satisfied.

For example, a service penetration or joint in the wall system may not be sealed but the barrier could still be effective and maintain tenable conditions in an adjacent area for the required time.

Therefore, a single reliability value will not be specified but a performance distribution will be derived from which the effectiveness can be determined for relevant scenarios as part of the fire engineering analysis as described in Section 1.4.

1.4 Estimates of Performance Distributions for Smoke Barrier Systems

The performance distribution for a smoke barrier will vary with the application and this is best demonstrated by the following examples. In all cases the selected distributions should be agreed with the relevant stakeholders during the PBDB process.

1.4.1 Smoke Barrier with no Service Penetrations and all the Barrier Visible

This example could apply to a wall system separating enclosures where the wall spans between floor slabs and there is no false ceiling or concealed areas of wall.

Under these circumstances, a distribution could be assumed recognising that the range of potential leakages could vary from tight, average and loose construction as shown in Table 3. In this instance the distribution is referenced by a three-point representation, but other distributions could be selected based on the specific circumstances.

Table 3 Area Ratios Smoke Barrier with no Service Penetrations and all the Barrier Visible

Tightness	Area Ratio $A/A_W \times 10^{-4}$	Probability
Tight	0.15	0.25
Average	1.0	0.5
Loose	3.5	0.25

The effectiveness can then be determined by smoke modelling. A practical approach is to model the highest Area Ratio first and if the performance criteria for effectiveness are satisfied no further analysis is required.

1.4.2 Smoke Barrier with Service Penetrations and all the Barrier Visible

This example applies to separating enclosures where the wall spans between floor slabs and there is no false ceiling or concealed areas of wall, but service penetrations are present.

If it is reasonable to assume that any openings around services would be sealed to maintain acoustic separation and privacy, the distribution provided in Table 4 could be considered for adoption.

The effectiveness can then be determined by smoke modelling. A practical approach is to model the highest Area Ratio first and if the performance criteria for effectiveness are satisfied no further analysis is required.

Table 4 Area Ratios Smoke Barrier with Service Penetrations and all the Barrier Visible

Tightness	Area Ratio $A/A_W \times 10^{-4}$	Probability
Tight	0.2	0.25
Average	1.5	0.5
Loose	5.5	0.25

1.4.3 Smoke Barrier Partially Concealed with Service Penetrations

This example could apply to a wall system separating enclosures where there is a false ceiling that allows the passage of some but conceals service penetrations and the upper part of the barrier from visual observation. This type of arrangement would be expected to significantly increase the risk of service penetrations being unprotected and areas of the smoke barrier being omitted.

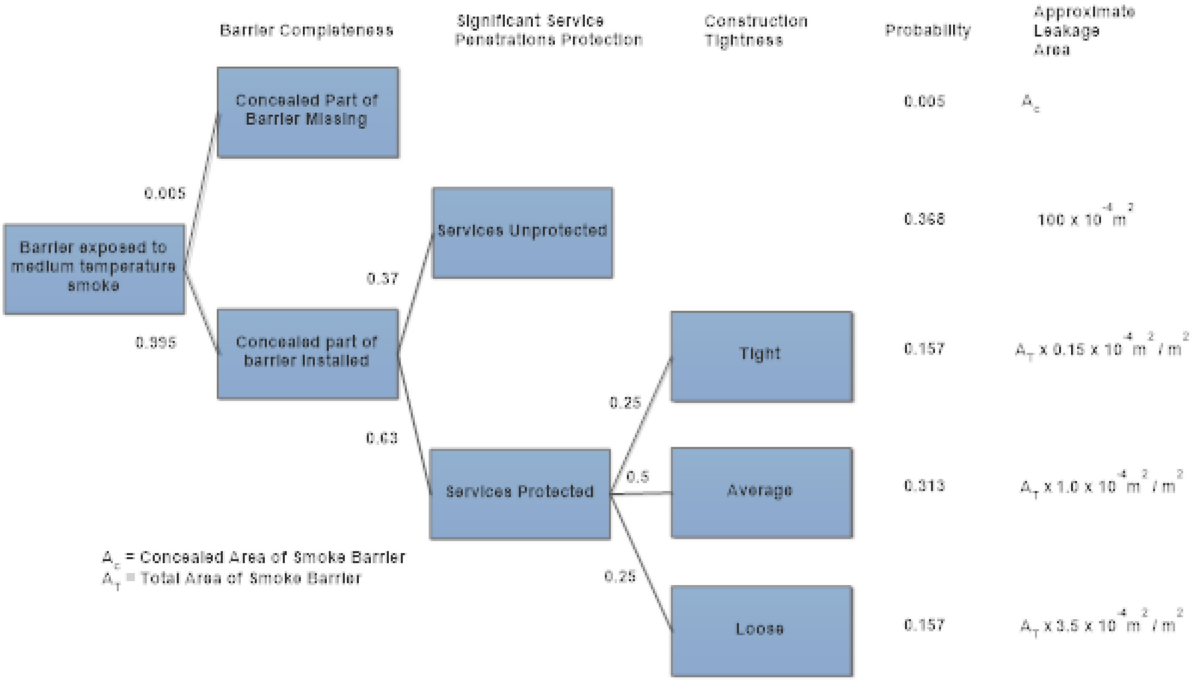
Table 5 provides estimates of typical leakage areas and probabilities of occurrence for significant smoke barrier defects based on the limited data available that is summarised in Appendix A.

Table 5 Typical Probabilities of Unprotected Service Penetrations and Concealed Sections of a Smoke Barrier

System	% unprotected	Modification to performance
Small penetration (e.g. single cable)	17	Included in distribution for loose airtightness
Large penetration (e.g. cable tray)	37	Add free area of 100 x 10^{-4} m^2 for each unprotected penetration
Collar system	10	Add free area of 100 x 10^{-4} m^2 for each unprotected penetration
Concealed smoke barrier	0.5	Assume total concealed area is open unless a smaller area can be justified

An example of a performance distribution that could be developed for a barrier with a single large service penetration occurring in a concealed space is shown in the form of an event tree (see Figure 1). The effectiveness can then be determined by modelling smoke spread using the appropriate leakage areas.

Figure 1 Example Derivation of Performance Distribution for a Smoke Barrier using an Event Tree.

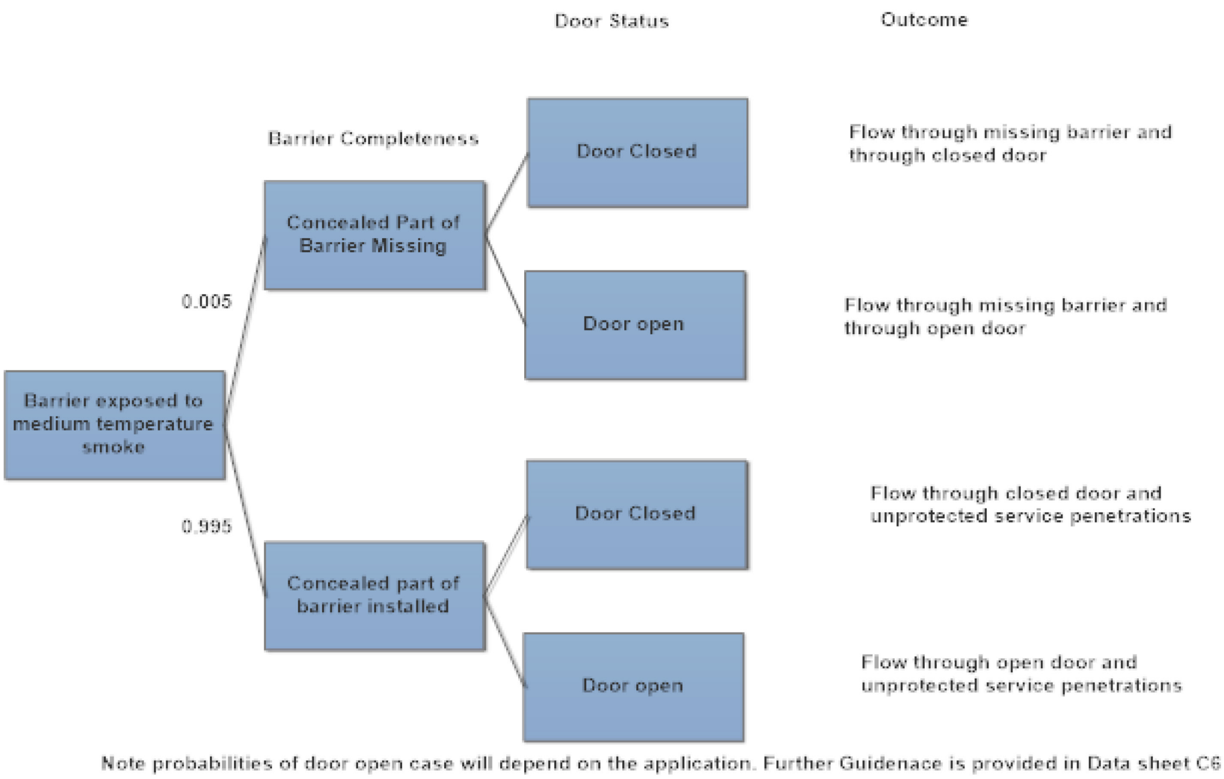


1.4.4 Smoke Barrier with Smoke Doors or Dampers

Where smoke dampers or smoke doors are provided, smoke leakage substantially greater than the base performance of the smoke barrier may occur even if the smoke doors and dampers close effectively and perform to a level equivalent to the NCC DTS provisions. Under these circumstances the smoke hazard management system will need to be designed to address substantially higher leakage rates than a smoke barrier even if some unprotected service penetrations are present.

An event tree can again be used to develop a performance distribution, but the tree can be simplified in most circumstances as shown in Figure 2 by adding a nominal leakage level for the barrier system assuming unsealed service penetrations (if services are present) to both the door open and door closed cases.

Figure 2 Example Derivation of a Performance Distribution for a Smoke Barrier Using an Event Tree



A.1 Appendix A Probability of Defects and Quantification of Impact

A.1.1 Service Penetrations

A.1.1.1 Marsh Ltd 2012 New Zealand Survey Results[10]

A report by Marsh Pty Ltd (Marsh 2012) [10] on the fire system effectiveness in major buildings in New Zealand included inspection data from university, hospital, and office / retail buildings relating to over 5000 passive fire protection systems including service penetrations which are summarised in Table 6. Whilst these observations relate to fire resistant construction in the absence of any better data, they provide a reasonable basis to estimate the probability of unprotected penetrations through smoke barriers.

Table 6 Summary of NZ Inspections of Service Penetration Seals

System	% of cases in drywall systems (e.g. plasterboard)	% of cases in masonry walls	Mean cases all elements %
Small penetration (e.g. single cable): Unsealed	16.2	18.4	17.3
Small penetration (e.g. single cable): Incorrect sealant	2.7	2.1	2.4
Small penetration (e.g. single cable): Total	18.9	20.5	19.7
Large penetration (e.g. cable tray): Unsealed	40.0	33.3	36.7
Large penetration (e.g. cable tray): Ad hoc arrangement	20.0	8.3	14.2
Large penetration (e.g. cable tray): Total	60	41.6	50.8
Collar system: missing	10.8	8.3	9.6
Collar system: Incorrect installation	7.7	6.3	7
Collar system: Ad-hoc arrangement	5.4	4.2	4.8
Collar system: Total	23.9	18.8	21.4

From Table 6, the frequencies of issues and types of faults with penetration seals in masonry and drywall systems are broadly similar. It cannot be ascertained if the higher frequency for plasterboard systems is a trend or just a result of the small sample size and therefore a mean of the plasterboard and masonry values has been calculated.

The ad-hoc arrangements category is assumed to represent penetrations that are sealed but there is insufficient documentation to determine the FRLs of the system. It will be assumed that these systems were reasonably sealed and will be resistant to temperatures up to 200°C and the range of leakage values proposed would be inclusive of these cases. The performance of smoke walls is likely to be less sensitive to incorrect sealant and incorrect installations compared to fire-resistant construction when exposed to high temperatures and therefore the data from Table 6 has been consolidated into Table 7 and typical opening areas have been estimated.

For a small single penetration, a 20 mm diameter service has been assumed with an open annular gap 6 mm wide. The open area for this configuration is approximately 500 mm^2 ($5 \times 10^{-4} m^2$). Therefore, provided there is less than one such penetration per square metre of wall area, it would be reasonable to assume these types of penetrations are addressed in the loose construction definition.

Considering large penetrations such as cable trays, a tray 300 mm wide was assumed to penetrate a 50 mm x 320 mm wide opening with 1/3 of the area filled with cables and the tray which equates to a free area of approximately 10,700 mm^2 ($107 \times 10^{-4} m^2$).

For collar systems, a uPVC pipe penetration has been selected as a reasonable worst-case scenario because the uPVC will tend to soften and collapse potentially leaving the majority of the opening unprotected. Penetration sizes will vary but a nominal 100 mm pipe size will be assumed to represent a larger common size assuming a 110 mm diameter opening remains if the pipe collapses. This corresponds to a free area of 9500 mm^2 ($95 \times 10^{-4} m^2$).

With no more detailed information available, based on these estimates a reasonable estimate for the free area presented by large penetrations or plastic pipe penetrations would be to assume a straight through opening approximately 10,000 mm^2 ($100 \times 10^{-4} m^2$).

Table 7 Seals with Potentially Significant Defects (Derived from Table 6)

System	% unprotected	Modification to performance
Small penetration (e.g. single cable)	17	Included in distribution for loose airtightness
Large penetration (e.g. cable tray)	37	Add free area of 100 x 10^{-4}m^2 for each unprotected penetration
Collar system	10	Add free area of 100 x 10^{-4}m^2 for each unprotected penetration

A.1.1.2 Moinuddin and Thomas Survey Findings[11]

Based on a survey of the annual inspection results from 11 Australian office buildings, Moinuddin and Thomas[11] estimated that every year, two unprotected holes could be expected for every three floors until they are repaired. These service penetrations were primarily located in the electrical and communication risers.

Specific data in relation to stair shaft inspections were obtained for three office buildings by Moinuddin and Thomas, and from these data, it was estimated that there is a 16% likelihood of having one gap / hole in each stair shaft.

Similarly, specific data in relation to lift shaft inspections for three buildings were obtained based on six inspection reports. No gap/hole was reported in the six reports.

Two more buildings had combined reports on fire-isolated shafts (both stair and lift):

- Building 1: had only one report stating, “Refit fire pillows where needed”, but this did not specify how many holes were found.
- Building 2: had 13 reports. One report stated “Various door latch hardware loose” and the other 12 reports had no problems.

The results from Moinuddin and Thomas cannot be directly compared to the Marsh Ltd survey results since the number of service penetrations in the buildings used for the Moinuddin and Thomas study was not reported. However, as the location was predominantly in electrical and communication risers, it would be reasonable to assume there would be a minimum of two large penetrations per floor. Assuming two large service penetrations per floor (six for three floors) for the Moinuddin and Thomas survey yields two unprotected penetrations from six; i.e. 33% of large penetrations would be unprotected which is consistent with the Marsh Ltd New Zealand Study.

Moinuddin and Thomas also included suggested values from earlier guides and studies which are summarised in Table 8.

Table 8 Estimates of Reliability of Walls from Various Sources Adapted from Moinuddin and Thomas[11]

Type of wall	Warringtonfire UK Delphi[1]	Fire Engineering Guidelines 1st edition[1]	BS DD240
Masonry	81%	95%	N/A
Gypsum	69%	95%	N/A
Concrete	N/A	95%	95%[2]

Notes:

1 Based on expert judgement.

2 Based on the assumption that it has 5% probability of having perforation before fire and no more gap is created during a fire.

A.1.2 Missing Sections of Barriers

There is potential for sections of smoke barriers to be omitted if they are located in concealed spaces and do not provide ready access for visual inspection.

Data directly relating to this defect could not be identified but the Moinuddin and Thomas[11] survey included the data presented in Table 9 relating to structural fire protection serving a critical role potentially located above a ceiling.

Table 9 Problems Reported During the Inspection of Fire Rated Materials from Moinuddin and Thomas[11]

Building No.	No. of floors	No. of reports available	No. of reports showing compliant	Problems reported
1	44	4	2	Report 1: At 6 locations the beam were found not protected Report 2: Non-compliant (no specific details)
2	18	1	0	Fire rated spray missing from a steel beam

Based on these two data points the number of elements with missing protection per floor would be between 0.06 and 0.136. The study does not identify the sizes of the buildings. A typical steel framed office approximately 63 m x 27 m could be expected to have of the order of 90 beams/ floor. Using this estimate the frequency of a gross defect would be approximately 0.0007 to 0.0015 / element. (i.e.0.07% to 0.15%).

These buildings were expected to reflect higher levels of compliance than the majority of buildings due to the commitment to the use of external audits and willingness to supply data. In addition assumptions were made in relation to the building configuration to derive the estimates. Therefore, having regard for the limited data available it is appropriate to apply a large factor of safety. Unless more relevant data is available it is suggested that the probability of a large area of smoke barrier being omitted within a concealed space would be 0.005 (0.5%) per element of construction representing a factor of safety of 3.33 on the highest estimate based on the limited data available.

A.2 Appendix B References

1. ABCB, National Construction Code 2019. 2019.

2. Standards Australia, AS 1530.4 Methods for fire tests on building materials, components and structures, Part 4: Fire-resistance tests for elements of construction. 2014, Standards Australia: Sydney.

3. ISO, ISO TR 5925-2 Fire Tests - Smoke -control door and shutter assemblies Part 2: Commentary on test methods and the applicability of test conditions and the use of test data in a smoke containment strategy. 2006, ISO: Switzerland.

4. Standards Australia, AS 1288-2006 Glass in buildings - Selection and installation 2006, Standards Australia: Sydney.

5. Klote, J.H. and J.A. Milke, Principles of smoke management. 2002: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

6. Standards Australia, AS 1530.7-2007 Methods for fire tests on building materials, components and structures Part 7: Smoke control assemblies—Ambient and medium temperature leakage test procedure. 2007, Standards Australia: Sydney.

7. Standards Australia, AS 6905 -2007 Smoke Doors. 2007, Standards Australia: Sydney Australia.

8. Standards Australia, AS 1682.1 Fire, smoke and air dampers Part 1: Specification. 2015, Standards Australia: Sydney.

9. Standards Australia, AS 1668.1 The use of ventilation and air conditioning in buildings Part 1: Fire and smoke control in buildings. 2015, Standards Australia: Sydney.

10. Marsh Ltd, Fire System Effectiveness in Major Buildings. 2012, Fire Service Commission: New Zealand.

11. Moinuddin, K.A. and I.R. Thomas. A survey to estimate the reliability of fire safety system components. in FSE09: Fire Safety Engineering International Conference: Charting the Course. 2009. Engineers Australia Society of Fire Safety.

Data Sheet C6 Fire Barrier System Effectiveness

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C6 addresses Fire Barrier Effectiveness, and should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1 General overview of the effectiveness of fire protection systems
- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C3 Detector Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness
- Data Sheet C5 Smoke Barrier Effectiveness
- Data Sheet C7 Smoke and Fire door Effectiveness

- Data Sheet C8 General Methods for Conversion of Fire Resistance Times.

Data Sheet C6 Contents

Version	Date	Data Sheet	Comments
C6-1	Jan 2019	C6	Initial draft for comment
C6-2	Jun 2019	C6	Draft for publication.

1.1 General Definition of Effectiveness

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Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note; Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*

- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

These definitions may not be appropriate for some passive fire protection systems and it may be more appropriate to define performance distributions as described in this Data Sheet.

1.2 Fire Barrier System

1.2.1 The Role of a Fire Barrier

Fire Barriers can be used as part of a fire and smoke containment strategy to limit the spread of fire and smoke to adjacent enclosures and / or paths of travel to *exits* for sufficient time to facilitate the safe evacuation of occupants and *fire brigade* intervention.

The barriers may be required to resist exposure to a range of conditions for varying durations depending on the fire severity, proximity to a fire and the role of the barrier or structural element in the building's fire safety strategy.

The exposure of a barrier is commonly expressed in terms of exposure to ambient, medium and high temperatures as described below for design and specification purposes:

- **Ambient temperature** - 20±10˚C
- **Medium temperature** - 200±20˚C
- **High temperature** – temperature representative of a *fully developed fire* (generally the standard heating regime or more severe hydrocarbon heating regime prescribed in AS 1530.4 are adopted for testing systems under standardised conditions [2]).

ISO TR 5925-2 [3] provides commentary relating to the applicability of these conditions and use of test data in a smoke containment strategy providing useful information for the development, analysis and specification of *Performance Solutions* involving smoke containment.

A barrier may be required to resist the spread of fire and smoke when exposed to one or more of the following conditions:

(a) Smoke at ambient and medium temperatures:

- during the early stages of a fire scenario
- when the barrier is distant from the fire
- a sprinkler-controlled fire.

Refer to Data Sheet C5 for the effectiveness of smoke barriers exposed to ambient and medium temperatures.

(b) Smoke and fire at high temperatures:

- during the *fully developed fire* / decay stages of a fire scenario for a nominated period to allow for evacuation and/or *fire brigade* intervention
- the total duration of the *fully developed fire* including the decay phase (resist the total *burnout* of contents)
- due to direct flame contact and / or radiant heat from large flaming fires, travelling fires close to a barrier and from sources external to a building.

This Data Sheet addresses the effectiveness of fire barrier systems (commonly referred to as fire resistant barriers) exposed to high temperatures.

1.2.2 Quantification and Specification of Fire Barrier Systems

The NCC DTS provisions relating to fire barriers are similar to those found in many national fire safety codes in that the required fire separation performance for a fire barrier exposed to high temperatures is generally expressed in terms of a fire resistance time or rating. The NCC adopts the term fire resistance level (FRL) which means the grading periods in minutes determined in accordance with AS 1530.4[2] for the following criteria:

- *structural adequacy*; and
- *integrity*; and
- *insulation*,

and expressed in that order.

A dash means that there is no requirement for that criterion.for example, FRL 90 / 60 / - means there is-

- a 90 minute requirement for an FRL for *structural adequacy*; and
- a 60 minute requirement for an FRL for *integrity*; and
- no requirement for an FRL for *insulation*.

Other criteria may also be applied by AS 1530.4 or related methods, depending on the element being evaluated. Examples include:

- the resistance to the incipient spread of fire
- radiant heat flux
- the period for which a critical service (e.g. emergency power supply cable) maintains its design function.

Major advantages of the use of FRLs include:

- it provides a method for specifying the performance of fire barriers in a consistent manner that is compatible with the DTS approach
- the performance of fire barriers can be easily verified using a *Standard Fire Test* (AS 1530.4) providing product developers and suppliers with a clearly defined pathway to obtaining appropriate evidence of suitability

- availability of codified calculation methods for calculating the FRL of elements of construction; typical examples are provided in structural design codes such as AS 4100 [3], AS 3600 [4] and AS 1720.4 [5]
- enables the performance of fire barriers incorporating features such as service penetrations, fire doors and other protected openings to be evaluated by test where first principle calculations would be impractical or inaccurate.

The major limitation with the use of FRLs is that the performance of fire barriers is normally determined by exposing an element to only the standard heating regime prescribed in AS 1530.4. The performance of a barrier if exposed to other conditions (heating regimes), that may be more representative of a *design scenario* being evaluated as part of a fire engineering analysis, is generally not directly determined. Some fire barriers may be sensitive to exposure to different rates of heating and heating conditions, and if the barrier forms part of the building structure, temperature induced deflections and stresses can initiate structural failures.

If the heating regime associated with a *design scenario* varies from the standard heating regime (which it will in most scenarios), it is necessary to convert FRLs to an equivalent scenario time when undertaking a fire engineering analysis. Whilst there are a range of methods that can be adopted for this conversion this process will introduce an increased level of uncertainty particularly if applied to barrier systems that are sensitive to differing heating conditions which should be considered when estimating the effectiveness of barrier systems. This uncertainty can be reduced if the results from tests using different heating regimes and / or data from natural fire experiments are available and can be used to validate the conversion process for barrier systems.

Reference should be made to Data Sheets B3 and C8 for further information.

For the purposes of this Data Sheet the performance of fire barriers will be expressed in terms of FRLs when determining effectiveness. Where the FRLs require conversion to scenario time the uncertainty associated with the conversion should be accounted for during the analysis to the degree necessary. Since a comparative approach is adopted by the FSVM, in some circumstances, the uncertainty associated with this conversion may be less critical particularly if the same barrier system is used for the proposed *Performance Solution* and *reference building*.

1.2.3 Applicability of AS 1530.4 Criteria

1.2.3.1 Structural Adequacy

Structural adequacy is defined as the ability of a loadbearing element of construction to support a load when tested in accordance with AS 1530.4. The *structural adequacy* criterion applies to loadbearing elements of construction including fire barriers such as walls and floors. A simple interpretation is that the *structural adequacy* time represents the time to failure of the element to support the applied load during the test although other criteria such as deflection limits and critical temperatures are applied in some cases.

The structural behaviour of buildings is generally more complex. For example, structural redundancy may facilitate load redistribution delaying failure of the element during a fire or thermally induced stresses may cause earlier failure of the element or whole structure particularly if substantial fire spread occurs heating a large number of members. These effects relate to the specific building configuration.

Estimates for efficacy with respect to *structural adequacy* within this Data Sheet relate to single elements of construction only and if appropriate should be modified to take account of the structural design of a building in application where the outcomes may be critically affected.

1.2.3.2 Integrity

Integrity is defined as the ability of an element of construction to resist the passage of flames and hot gases from one space to another when tested in accordance with AS 1530.4.

Performance under the criteria of *integrity* as defined by AS 1530.4 is determined if:

- a cotton pad applied over an opening crack or fissure is ignited (includes glowing and flaming)
- the presence of a through gap larger than 150 mm x 6 mm or 25 mm diameter
- sustained flaming on the surface of the unexposed face (non-fire side) for 10s or longer.

If *combustible* materials including linings are close to the position of an opening crack or fissure, fire spread to the non-fire side could occur at approximately the time of the *integrity* failure when exposed to the standard heating regime. If no combustibles are close to the opening the timing of fire spread could be significantly longer depending upon the extent of the *integrity* failure and specific details of a building.

Estimates for efficacy with respect to *integrity* in this Data Sheet relate to failure under the criterion of *integrity* of AS 1530.4. If appropriate, the timing of fire spread could be modified to take account of a specific building design where the outcomes may be critically affected.

1.2.3.3 Insulation

Insulation is defined as the ability of the surface of an element of construction not exposed to the furnace to maintain a temperature below the following specified limits when tested in accordance with AS 1530.4:

- average temperature of the unexposed face of the specimen exceeds the initial temperature by 140 K; or
- maximum temperature at any location on the unexposed face of the test specimen exceeds the initial temperature by more than 180 K.

These are below the temperature of unpiloted ignition of most materials over a short period of time but are measured with the surface of the specimen not exposed to the furnace relatively clear of obstructions allowing convective cooling. If *combustible* materials with insulating properties are in contact with the surface the interface temperature could be higher and therefore the timing of fire spread could be modified.

Estimates for efficacy with respect to *insulation* in this Data Sheet relate to failure under the criterion of *insulation* of AS 1530.4. If appropriate the timing of fire spread could be modified to take account of a specific building design where the outcomes may be critically affected.

1.2.3.4 High Temperature Smoke Spread

The spread of hot gases / smoke through elements of construction is generally not measured directly or indirectly during AS 1530.4 tests except where modifications to the test procedures are implemented to gather additional information.

When undertaking fire engineering analyses to determine the outcomes of a *design scenario* it may be necessary to model the spread of hot gases; for example, from a *fully developed fire* in an enclosure to an adjoining corridor providing a path of travel to an *exit*.

Under AS 1530.4, there is a variation to the general principles for fire dampers and air grilles within ducts where the *integrity* criteria of AS 1530.4 is modified to apply a limit to the leakage through the damper of 360 $m^3/(h/m^2)$ corrected to standard temperature and pressure. Measurements of actual leakage rates are required to be reported during the tests which may demonstrate a significant safety margin compared to the prescribed leakage limit in some cases.

For other elements of construction forming a barrier or part of a barrier it is generally necessary to exercise considerable expert judgement to estimate smoke spread (and smoke production) from barriers. Further general guidance is provided in Section 1.5 and specifically for fire doors in Data Sheet C7.

1.3 Overview of Effectiveness of Fire Barrier Systems

1.3.1 Adaptation of General Definitions of Effectiveness

1.3.1.1 Application of Efficacy to Fire Barrier Systems

For the purposes of the Group C Data Sheets, efficacy is defined as the degree to which a system achieves an objective given that it performs to a level consistent with the system specification. The criteria for efficacy for fire barrier systems can be expressed, for example, as the probability that the system will retard the spread of fire and smoke through the barrier to maintain tenable conditions in an adjacent enclosure until evacuation is complete, to facilitate *fire brigade* intervention and to limit damage to other property.

In many cases the achievement of this objective is dependent on the performance of other fire protection systems and building configurations. For the purposes of determining the efficacy of fire barriers in this Data Sheet the impact of material variations and installation procedures on the FRL of the barrier system will be considered.

Where necessary these estimates may require modification on a case by case basis, based on the fire modelling undertaken as part of the fire engineering analysis and to take account of factors such as variations in fire severity and safety factors adopted. For example, the efficacy of a fire barrier will be substantially lower if an 80-percentile *fire load* is assumed compared to a 95 or 99-percentile *fire load* unless the reduction is offset by other fire safety measures.

1.3.1.2 Application of Reliability to Fire Barrier Systems

The concept of reliability can be relatively easily applied to components such as fire doors and fire dampers within a fire barrier system where failure of an element to close or be closed when required to be in the closed position clearly represents a failure of the system.

The probability of full closure and if appropriate latching can therefore be used to define the reliability of fire doors and fire dampers. If necessary, the probability of closure can be adjusted to account for errors in the manufacture and installation that could cause a major premature failure of the fire door or smoke damper to provide a modified reliability value. The reliability of these components is dealt with in more detail in Data Sheets C7 and C4 respectively.

The application of the concept of reliability to fire barriers with and without service penetrations is more complex because the significance of defects will vary from case to case and may not significantly impact in smoke spread or fire spread.

For example:

- failure under the criterion of *insulation* for small service penetrations or joints in a wall system may not significantly impact the ability of the barrier to prevent the spread of fire and smoke
- a section of cladding protecting structural members may not be critical if the structural members have high levels of inherent fire resistance.

1.3.1.3 Adoption of a Performance Distribution to Define Effectiveness

For fire barriers, single probability values for reliability and efficacy will not be specified but a performance distribution will be derived for the FRL of a barrier system from which the effectiveness can be determined for *design scenarios* as part of the fire engineering analysis as described in Section 1.4.

1.4 Estimates of FRL Performance Distributions for Fire Barrier System Effectiveness

The performance distribution for a fire barrier will vary with the application and this is best demonstrated by the following examples. In all cases the selected distributions should be agreed with the relevant stakeholders during the PBDB process.

1.4.1 Base Fire Barrier with No Service Penetrations

The following examples could apply to wall systems separating enclosures where the wall spans between floor slabs and there is no false ceiling or concealed areas of wall.

Under these circumstances, a distribution can be derived addressing typical variations in material properties and construction and any gross or major defects that could significantly compromise the performance of the fire barrier. Two examples will be considered based on room and furnace tests of fire rated constructions undertaken by the Fire Code Reform Centre (FCRC) [4].

Example 1 Plasterboard Wall Systems - 1 x 16mm fire protective grade plasterboard applied to steel studs

A series of six partition tests of similar construction, comprising one layer of fire protective grade plasterboard applied to steel studs, were undertaken on non-loadbearing partitions by two different laboratories. These were non-loadbearing tests. Three tests were performed on partitions constructed in accordance with standard specifications and three representing bad construction practice with a 10 mm gap between two sheets that was filled with plaster, some screw heads penetrating the paper, some screws too close to the edge of the board and some screws at larger centres. Further details are provided in FCRC report PR99-01 [4].

The results from the six tests are summarised in Table 2. Collapse of the sheeting followed closely after failure under the criteria of *integrity* due to flaming on the unexposed side.

The results indicate that the performance of the tested systems was slightly sensitive to the installation faults simulated. If normal distributions are assumed the standard deviation of the results were found to be 2.9 minutes for *insulation* and 2.7 minutes for *integrity*.

Table 2 Fire Resistance Test Results on Similar Plasterboard Constructions with Varying Quality of Installation Derived from FCRC[4].

Installation Quality	Insulation –mins	Integrity - mins
Standard	75	109
Bad	75	112
Standard	76	110
Bad	70	106
Bad	75	107
Standard	79	105
Mean	75	108
Max	79	112
Min	70	105

A series of tests were performed at 16 laboratories in North America and Japan to ASTM E119 which is broadly similar to AS 1530.4 on a partition system constructed from the same batch of materials and to similar standards. The results were reported by Manzello and Mizukami [5].

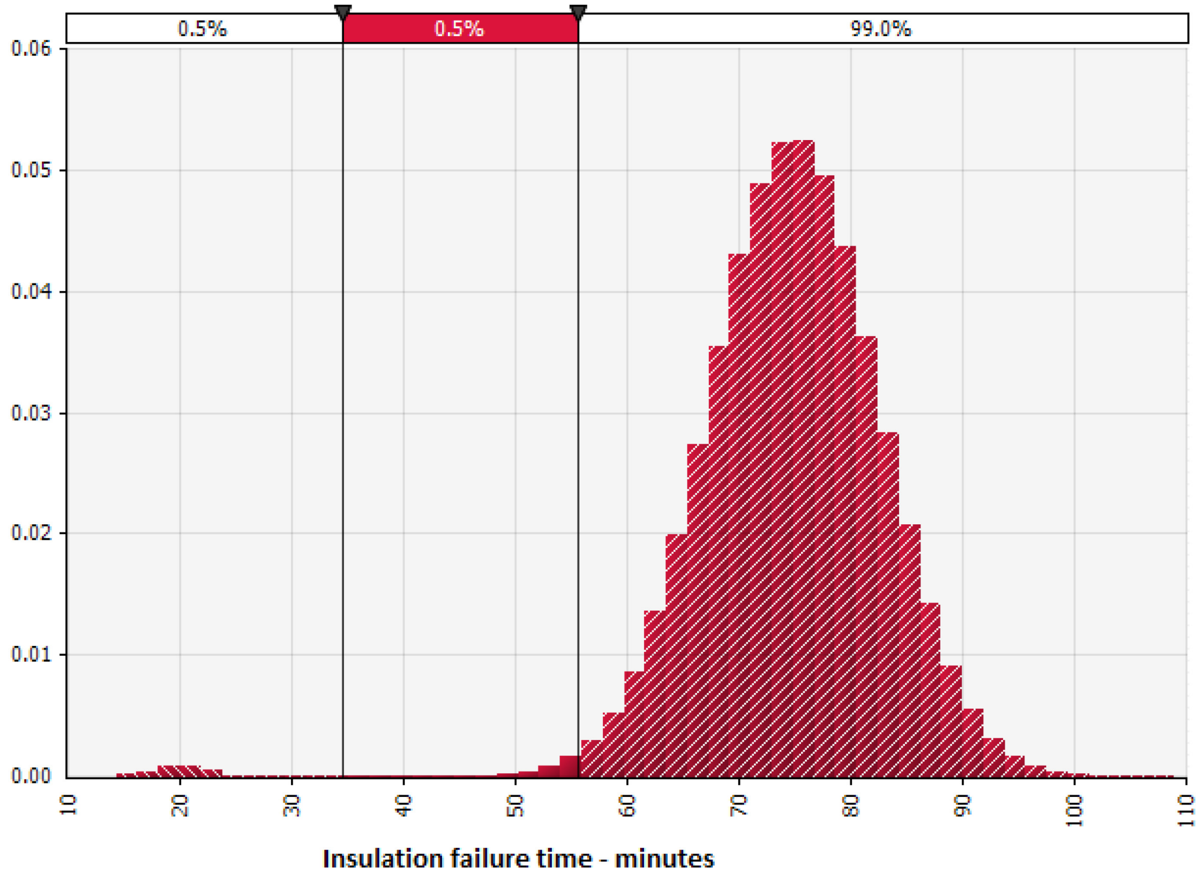
The average failure time for the six Japanese laboratories was 67.1 minutes with a standard deviation of 1.1 minutes and for the ten North American laboratories the average failure time was 65 minutes with a standard deviation of 2.8 minutes. These results did not include boards from a range of manufacturers which would be expected to increase the variability further.

For this example, the standard deviation has been assumed to be 10% of the mean value and the performance of the plasterboard wall system without gross defects based on the *insulation* criteria will be a mean of 75 minutes with a standard deviation of 7.5 minutes.

The above distribution requires adjustment to address gross defects which should be determined in consultation with the PBDB stakeholders. In this example, for demonstration purposes the most likely gross defect for the configuration and form of construction was assumed to be substitution of the fire protective grade plasterboard with non-fire grade plasterboard with expected *insulation* performance of 20 minutes and a standard deviation of 2 minutes with a probability of occurrence of 0.5% per wall.

The two distributions derived above can be combined to provide a performance distribution as show in Figure 1 Example Derivation of Performance Distribution for a Smoke Barrier using an Event Tree. This distribution is typical of a system where there is a significant safety margin of 15 minutes for a plasterboard wall system that is required to achieve an FRL of 60/60/60 with the 1-percentile value occurring after exposure to the standard fire resistance heating regime for 55.7 minutes. It should be noted that without a safety margin the probability of the FRL being below the specified FRL could be approximately 0.5 (50%).

Figure 1 Example Performance Distribution for a Plasterboard Partition with Mean FRL for Insulation of 75 Minutes and a 0.5% Probability of a Gross Defect with an FRL of Insulation of 20 Minutes.



Example 2 Masonry Wall 110 mm thick constructed using 230 mm long x 110 mm wide x 76 mm high ordinary dry pressed common bricks

A series of six non-loadbearing masonry wall tests were performed using bricks from the same supplier. The walls were 110 mm thick constructed using 230 mm long x 110 mm wide x 76 mm high ordinary dry pressed common bricks laid up in stretcher bond using a mortar mixture comprising one-part type A Portland cement, one-part lime and six parts bush sand.

Three tests were performed on walls constructed in accordance with standard specifications representing standard / good construction practice and three representing bad construction practice. The principal difference between the standard-workmanship wall and the bad-workmanship wall was the application of mortar at the perpends and bed joints. For the bad-workmanship walls there was a lack of mortar to a depth of approximately 5-15 mm over approximately 40-50 % of the perimeter of the bricks.

Further details are provided in FCRC report PR99-01 [4]. The results from the six tests are summarised in Table 3.

Table 3 Fire Resistance Test Results on Similar Masonry Walls with Varying Quality of Installation Derived from FCRC[4]

Installation Quality	Insulation – mins	Integrity - mins	Structural Adequacy -mins	Initial Failure - mins
Standard	103	>241	>241	103
Standard	104	>241	>241	104
Standard	107	220	>241	107
Mean - Standard	N/A	N/A	N/A	105
Bad	76	46	95	46
Bad[1]	98	147	147	98
Bad	75	81	81	75
Mean - Bad	N/A	N/A	N/A	73

Note: The FCRC report identified that the specimen was nominally “bad construction” however it was judged to be of better construction than the other bad construction masonry walls.

The results indicate that the performance of the masonry system was sensitive to the magnitude of the installation faults and the mode of failure varies when defects are introduced.

If the probability of faults and magnitude of the faults is known a performance distribution can be developed in a similar manner to the plasterboard partition shown in Figure 1 Example Derivation of Performance Distribution for a Smoke Barrier using an Event Tree.

1.1 Fire Barrier with Service Penetrations

Table 4 provides estimates of the probabilities of occurrence of significant defects with the protection of service penetrations based on the limited data available that is summarised in Appendix A.

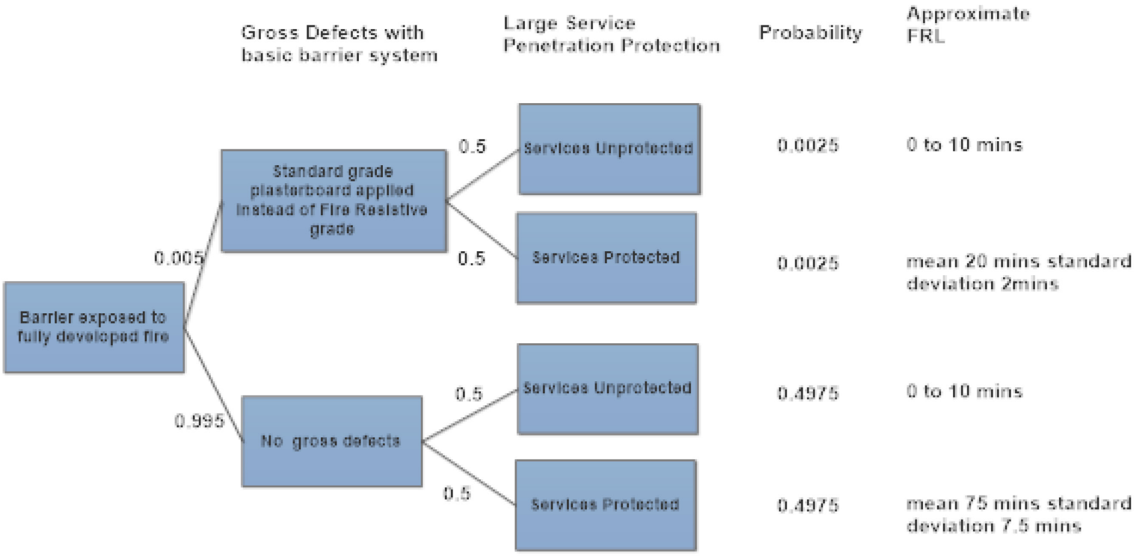
Table 4 Typical Probabilities of Unprotected Service Penetrations in Commercial Buildings

System	% unprotected
Small penetration (e.g. single cable)	20
Large penetration (e.g. cable tray)	50
Collar system	20

The impact of these defects on the FRL will vary but generally the FRL would be in the range of 0 to 10 minutes if these defects were present.

An example of a performance distribution that could be developed for a barrier with a single large service penetration occurring is shown in the form of an event tree assuming a correctly installed and maintained service penetration will not compromise the performance of the fire barrier (see Figure 2).

Figure 2 Example Derivation of Performance Distribution for a Smoke Barrier using an Event Tree.



The NCC DTS provisions for service penetrations relax the FRL requirement for *insulation* for service penetrations in some instances. In applications where such reductions in *insulation* performance are not considered critical the *integrity* criteria may be selected to define the fire resistance performance of the service penetrations systems if suitably protected.

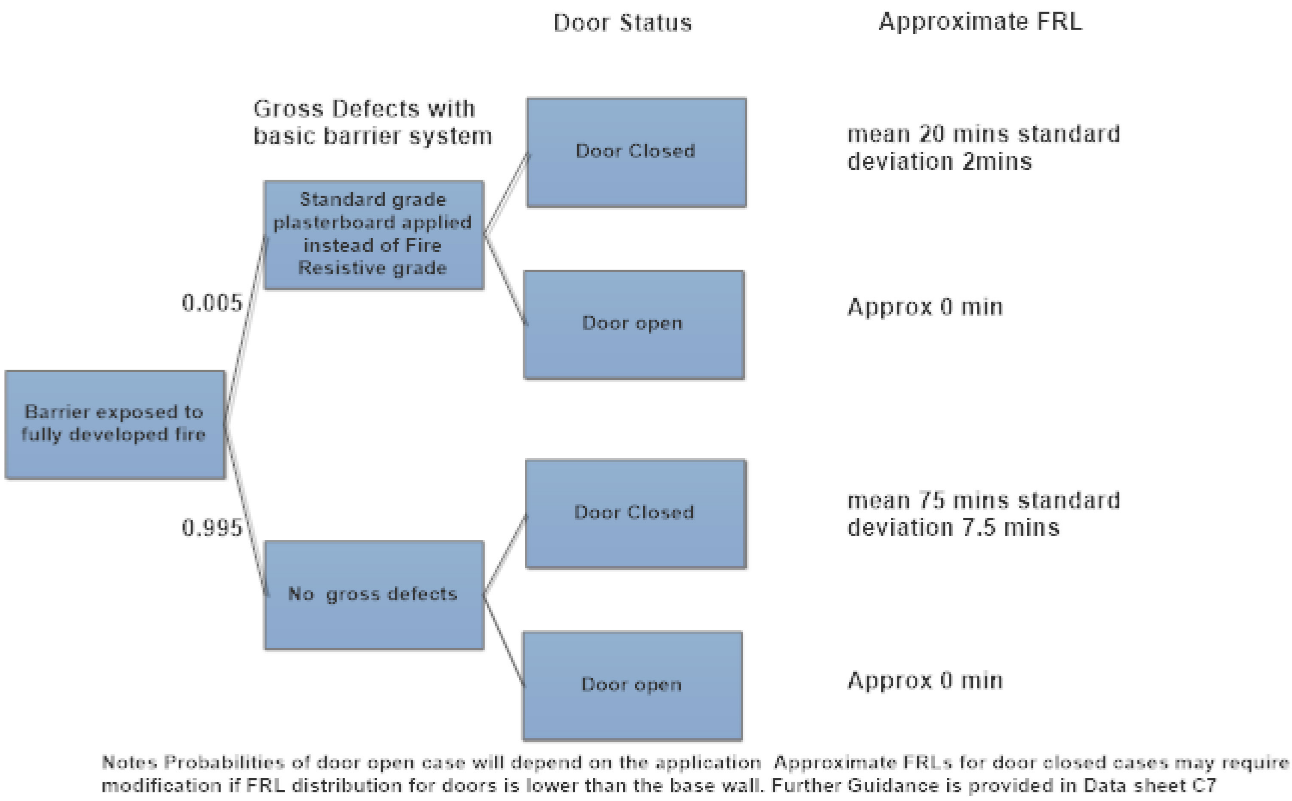
1.2 Fire Barrier with Fire Doors or Fire Dampers

Where fire dampers or fire doors are provided the reliability of the self-closure systems can have a significant impact on the performance of the fire barrier in which they are mounted.

An event tree can again be used to develop a performance distribution, as shown in Figure 3.

The NCC DTS provisions for fire dampers and fire doors generally relax the FRL requirement for *insulation* in recognition that *combustible* materials are unlikely to be placed directly in front of the door or a fire damper located within a *non-combustible* duct. In applications where such reductions in *insulation* performance are not considered critical the *integrity* criterion is normally selected to define the fire resistance performance of the door or damper.

Figure 3 Example Derivation of a Performance Distribution for a Fire Barrier Incorporating a Smoke Door using an Event Tree.



1.5 Smoke Spread Through Fire Barriers

1.5.1 Spread of Smoke – High Temperature Gases

The spread of hot gases / smoke through elements of construction is generally not measured directly or indirectly during AS 1530.4 tests unless modifications to the test procedures are implemented.

The exception to this is the testing of fire dampers and air grilles within ducts where the *integrity* criteria of AS 1530.4 is modified to apply a limit to the leakage through the damper of 360 m^3/ (h/m^2) corrected to standard temperature and pressure. Measurements of actual leakage rates are required to be reported during the tests which may provide a significant safety margin compared to the prescribed limit.

For other elements it is generally necessary to exercise expert judgement to estimate smoke spread, smoke production rates and / or leakage areas based on technical literature and observations from fire tests. The following sections provide general guidance and Data Sheet C7 provides specific guidance relating to fire / smoke doors. Reference should also be made to Data Sheet C5 for background information relating to flow areas.

1.5.2 Fire / High Temperature Smoke Barrier With No Service Penetrations or Doors

If a fire resistance test report contains detailed observations of smoke production / release and / or visual records it may be possible to determine the timing at which smoke spread from the barrier increases above expected background values. This timing should be cross-checked against temperature measurements from the specimen, observations of cracks and deflections and consideration of material properties.

Prior to a significant increase in smoke production / spread it may be reasonable to apply the leakage areas in Table 8 which were derived from tests performed at ambient temperatures. Refer to Data Sheet C 5 for further information on the derivation of Table 5.

Once the smoke production / spread increases based on the data available the flow areas should be increased.

Table 5 Area Ratios Smoke Barrier With No Service Penetrations and All the Barrier Visible

Tightness	Area Ratio $A/A_W \times 10^{-4}$	Probability
Tight	0.15	0.25
Average	1.0	0.5
Loose	3.5	0.25

Notes:

1. Flow areas based on C=0.65 when flows measured at ambient temperatures with a pressure differential of 75Pa

2. A/A_W is the flow area per unit area of the wall or floor.

1.5.3 Fire / High Temperature Smoke Barrier With Service Penetrations

After a penetration system fails or there is a significant installation error a conservative approach is to assume an opening exists through the barrier of the same dimensions as the service penetration and associated seal / fire protection device unless more detailed information is available.

Prior to failure of a penetration system (as for the barrier described above) test data should be reviewed and prior to an observable increase in smoke spread if all service penetrations are smoke sealed, the values for loose construction in Table 2 could be applied.

Once the smoke production / spread increases based on the data available the flow areas should be increased.

It should be noted that some service penetrations may release significant quantities of smoke for a short period at the start of fire test prior to closure. In these circumstances if adequate data is available the flow area can be adjusted to reflect this behaviour.

A.1 C6 Appendix A Probability of Defects and Quantification of Impact of Defects

A.1.1 Service Penetrations

A.1.1.1 Marsh Ltd 2012 New Zealand Survey Results[12]

A report by Marsh Pty Ltd, Marsh 2012 [12] on the fire system effectiveness in major buildings in New Zealand included inspection data from university, hospital, and office / retail buildings relating to over 5000 passive fire protection systems including service penetrations which are summarised in Table 6.

Table 6 Summary of NZ Inspections of Service Penetration Seals

System	Issue	% of cases in drywall systems (e.g. plasterboard)	% of cases in masonry walls	Mean cases all elements %
Small penetration[1]	Unsealed	16.2	18.4	17.3
Small penetration[1]	Incorrect sealant	2.7	2.1	2.4
Small penetration[1]	Total	18.9	20.5	19.7
Large penetration[2]	Unsealed	40.0	33.3	36.7
Large penetration[2]	Ad hoc arrangement	20.0	8.3	14.2
Large penetration[2]	Total	60	41.6	50.8
Collar system	Missing	10.8	8.3	9.6
Collar system	Incorrect installation	7.7	6.3	7
Collar system	Ad-hoc arrangement	5.4	4.2	4.8
Collar system	Total	23.9	18.8	21.4

Notes:

1 For example, a single cable penetration.

2 For example, a cable tray penetration.

From Table 6 the frequencies of issues and types of faults with penetration seals in masonry and drywall systems are broadly similar. It cannot be ascertained if the higher failure frequency for plasterboard systems is a trend or just a result of the small sample size and therefore a mean of the plasterboard and masonry values has been calculated.

The ad-hoc arrangement category is assumed to represent penetrations that are sealed but there is insufficient documentation to determine the FRLs of the system. It will be assumed that the majority of these installations will be ineffective at high temperatures. Data from Table 6 has been consolidated into Table 7 and typical opening areas have been estimated.

For a small single penetration, a 20 mm diameter service has been assumed with an open annular gap 6 mm wide. The open area for this configuration is approximately 500 mm^2 (5 x $10^{-4}m^2$). Therefore, provided there is less than one such penetration per square metre of wall area, it would be reasonable to assume these types of penetrations are addressed in the loose construction definition.

Considering large penetrations such as cable trays, a tray 300 mm wide was assumed to penetrate a 50 mm x 320 mm wide opening with 1/3 of the area filled with cables and the tray which equates to a free area of approximately 10,700 mm^2 (107 x$10^{-4}m^2$).

For collar systems, a uPVC pipe penetration has been selected as a reasonable worst-case scenario because the uPVC will tend to soften and collapse potentially leaving the majority of the opening unprotected. Penetration sizes will vary but a nominal 100 mm pipe size will be assumed to represent a larger common size, i.e. assuming a 110mm diameter opening remains if the pipe collapses. This corresponds to a free area of 9500 mm^2 (95 x$10^{-4}m^2$).

With no more detailed information available, based on these estimates a reasonable estimate for the free area presented by large penetrations or plastic pipe penetrations would be to assume a straight through opening approximately 10,000 mm^2 (100 x$10^{-4}m^2$).

Table 7 **Seals with Potentially Significant Defects (Derived from Table 6)**

System	% unprotected	Modification to performance
Small penetration (e.g. single cable)	20	Included in distribution for loose airtightness
Large penetration (e.g. cable tray)	50	Add free area of 100 x $10^{-4}m^2$ for each unprotected penetration

System	% unprotected	Modification to performance
Collar system	20	Add free area of 100 x $10^{-4}$$m^2$ for each unprotected penetration

A.1.1.2 Moinuddin and Thomas Survey Findings[13]

Based on a survey of the annual inspection results from 11 Australian office buildings, Moinuddin and Thomas[13] estimated that every year two unprotected holes could be expected for every three floors until they are repaired. These service penetrations were primarily located in the electrical and communication risers.

Specific data in relation to stair shaft inspections were obtained for three office buildings by Moinuddin and Thomas, and from these data, it was estimated that there is a 16% likelihood of having one gap/hole in each stair shaft.

Similarly, specific data in relation to lift shaft inspections for three buildings were obtained based on six inspection reports. No gap/hole was reported in the six reports.

Two more buildings had combined reports on fire-isolated shafts (both stair and lift):

Building 1: had only one report stating, “Refit fire pillows where needed”, but this did not specify how many holes were found.

Building 2: had 13 reports. One report stated, “Various door latch hardware loose” and the other 12 reports had no problems.

The results from Moinuddin and Thomas cannot be directly compared to the Marsh Ltd survey results since the number of service penetrations in the buildings used for the Moinuddin and Thomas study was not reported. However, as the location was predominantly in electrical and communication risers, it would be reasonable to assume there would be a minimum of two large penetrations per floor. Assuming two large service penetrations per floor (six for three floors) for the Moinuddin and Thomas survey yields two unprotected penetrations from six; i.e. 33% of large penetrations would be unprotected which is consistent with the Marsh Ltd New Zealand Study.

Moinuddin and Thomas also included suggested values from earlier guides and studies which are summarised in Table 8.

Table 8 Estimates of Reliability of Walls from Various Sources Adapted from Moinuddin and Thomas[13]

Type of wall	Warringtonfire UK Delphi[1]	Fire Engineering Guidelines 1st edition[1]	BS DD240
Masonry	81%	95%	N/A
Gypsum	69%	95%	N/A
Concrete	N/A	95%	95%[2]

Notes:

1 Based on expert judgement.

2 Based on the assumption that it has 5% probability of having perforation before fire and no more gap is created during a fire.

A.1.2 Missing Sections of Barriers

There is potential for sections of fire barriers to be omitted if they are located in concealed spaces and do not provide ready access for visual inspection.

Data directly relating to this defect could not be identified but the Moinuddin and Thomas[13] survey included the data presented in Table 9 relating to structural fire protection serving a critical role potentially located above a ceiling.

Table 9 Problems Reported During the Inspection of Fire Rated Materials from Moinuddin and Thomas[13]

Building No.	No. of floors	No of reports available	No of reports showing compliant	Problems reported
1	44	4	2	Report 1: At 6 locations the beam was found not protected Report 2: Non-compliant (no specific details)
2	18	1	0	Fire rated spray missing from a steel beam

Based on these two data points the number of elements with missing protection per floor would be between 0.06 and 0.136. The study does not identify the sizes of the buildings. A typical steel framed office approximately 63 m x 27 m could be expected to have of the order of 90 beams/ floor. Using this estimate the frequency of a gross defect would be approximately 0.0007 to 0.0015 / element (i.e.0.07% to 0.15%).

These buildings were expected to reflect higher levels of compliance than the majority of buildings due to the commitment to the use of external audits and willingness to supply data. In addition, assumptions were made in relation to the building configuration to derive the estimates. Therefore, having regard for the limited data available, it is appropriate to apply a large factor of safety and unless more relevant data is available it is suggested that the probability of a large area of fire barrier being omitted within a concealed space would be 0.005 (0.5%) per element of construction representing a factor of safety of 3.33 on the highest estimate based on the limited data available.

A.2 C6 Appendix B References

1. ABCB, National Construction Code 2019. 2019.

2. Standards Australia, AS 1530.4 Methods for fire tests on building materials, components and structures Part 4: Fire-resistance tests for elements of construction. 2014, Standards Australia: Sydney.

3. ISO, ISO TR 5925-2 Fire Tests - Smoke -control door and shutter assemblies Part 2: Commentary on test methods and the applicability of test conditions and the use of test data in a smoke containment strategy. 2006, ISO: Switzerland.

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Data Sheet C7 Smoke and Fire Door System Effectiveness

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the FSVM introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C7 addresses, Smoke and Fire Door Effectiveness of Hinged Doors since they are the most common types, It should be read in conjunction with the FSVM Handbook and other Group C Data Sheets which include:

- Data Sheet C1 General overview of the effectiveness of fire protection systems
- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C3 Detector Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness

- Data Sheet C5 Smoke Barrier Effectiveness
- Data Sheet C6 Fire Barrier Effectiveness
- Data Sheet C8 General Methods for Conversion of Fire Resistance Times

For other types of door and shutter assemblies such as sliding doors and roller shutters the same principles apply but criteria relating to *insulation* may vary and it may be more difficult to protect gaps in the door assemblies (e.g. around the barrel of a roller shutter) allowing significantly greater smoke spread.

Data Sheet C7 Contents

Version	Date	Data	Comments
C7-1	Jan 2019	C7	Initial draft for comment
C7-2	Jun 2019	C7	Draft for publication.

1.1 General Definition of Effectiveness

Definitions of Effectiveness, Efficacy and Reliability

Effectiveness is a combination of two factors, efficacy and reliability.

Efficacy is the degree to which a system achieves a design objective given that it performs to a level consistent with the system specification during the relevant fire scenario.

Note: Efficacy may vary depending on the fire scenario selected. Normal variations in materials or components (including deterioration over time) may have an impact on the efficacy of a fire protection system depending on the scenario under consideration, methods of analysis and safety factors adopted. Interactions with other fire protection systems forming part of a building's fire safety strategy should also be considered.

Reliability is the probability that a system performs to a level consistent with the fire protection system specification.

Note: Typical examples of matters for consideration when determining the reliability of fire protection systems include:

- common mode failures
- probability that active systems are unavailable due to failure of a component, isolation for maintenance / renovation, or inadvertent isolation of a system etc.
- unprotected openings in fire and smoke barriers that may prevent the system achieving its design objective
- large variations in material properties and component performance (including deterioration over time) that are not addressed under the criteria for efficacy and may prevent a system performing to a level consistent with the system specification
- quality control, levels of workmanship and commissioning / verification
- scope, frequency and quality systems applied to maintenance, inspection and testing throughout the building's life
- probability of fire and smoke doors chocked open
- probability of locked / obstructed *exits*

- probability of unprotected structural elements that should have been protected
- probability of substitution of nominated fire-resistant cladding / protection of wall / floors and structural elements by materials having a lesser performance
- probability of unauthorised substitution of *non-combustible* materials with *combustible* materials
- probability of unauthorised substitution of wall and ceiling linings with materials having a lesser performance.

The definitions adopted for the Group C Data Sheets are compared with other common definitions in Table 1 to assist comparison with data from other sources.

Table 1 Comparison of Critical Terms

Group C Data Sheet	NFPA Analysis of Sprinklers (Hall)	Application of Reliability Indices
Effectiveness	% sprinklers operated effectively	N/A
Efficacy	% sprinklers effective if they operated	Structural reliability / reliability indices
Reliability	% sprinklers operated	N/A

1.2 Reliability of Fire and Smoke Doors

1.2.1 Generic Values

For most applications it is reasonable to consider the reliability of fire and smoke doors as the probability that the door will be closed when required to prevent the spread of fire and smoke.

If necessary, the probability that a door is closed can be adjusted to account for errors in the manufacture and installation that could cause a substantial premature failure of the fire door or smoke door to provide a modified reliability value.

Generally, fire and smoke doors are required to be *self-closing* or *automatic* closing.

The following definitions are adapted from the NCC with additional information relating specifically to fire and smoke doors:

- *Self-closing* means equipped with a device which returns the door to the fully closed (and latched) position immediately after each opening.
- *Automatic* means designed to operate when activated by a heat, smoke or fire sensing device. Typical *automatic*-closing arrangements for fire and smoke doors comprise an *automatic* hold open device fitted to a *self-closing* fire door such that upon activation of the sensing device the door will be released and close under the action of a door closer.

The probability of a fire or smoke door being closed during a scenario is dependent on many factors including:

- its position in the building and use
- the design / specification and quality of the self-closure devices and other hardware
- installation and maintenance of the doorset including door hardware
- building / occupant management which influences the frequency of door chocking and / or damage to door assemblies
- for *automatic* doorsets, operation of the release mechanism
- operation of the fire detection system
- air flows and pressure differentials within the building that may affect closure
- human interactions.

From the data presented in Appendix A, and if there is no other appropriate data, the following generic values for hinged doors maintained to high standards can be considered subject to agreement of the PBDB stakeholders.

Table 2 Generic Values for Hinged Doors Maintained to High Standards

Ref	Application	Reliability (probability of door leaf closed)
A	Door to fire stair or smoke enclosed stairways	0.9
B	Fire / smoke door in general path of travel	0.9
C	As A or B but with *automatic* operation	0.85
D	Door to SOU if closed at the start of a scenario and not opened by occupants	0.98

Ref	Application	Reliability (probability of door leaf closed)
E	Door to SOU of fire origin	See below

Note: The above values do not allow for failure of the detection system or impact of adverse air flows and pressure differentials.

The above values assume fire doors are specified, constructed and installed fully in accordance with AS 1905.1[2], smoke doors are specified, constructed and installed fully in accordance with AS 6905 [3] and all doorsets are maintained in accordance with AS 1851 [4]. Procedures should be implemented to inform occupants of the importance of fire and smoke doors and systems in place to report faults and take corrective actions promptly. Where there is reasonable doubt that these requirements will be met, lower values for reliability should be selected having regarded for the specific building and management systems expected.

1.2.2 Modification of Generic Values for SOU Doors

In Class 2 buildings and some Class 3 buildings, SOU doors would normally be in the closed state for security and privacy purposes. Under these circumstances issues such as chocking doors open would be less likely to occur and there would be a high probability of the initial state of the door being closed irrespective of whether a closer is operational or not. There would therefore be a higher initial probability of the door being initially closed.

The probability of the door being initially closed and remaining closed or being returned to the closed position after use will depend upon the *design scenario* being considered.

The following example has been included to demonstrate a typical approach, but the estimated probabilities and approach should be agreed by the PBDB stakeholders having regard for the specific building and in-use performance.

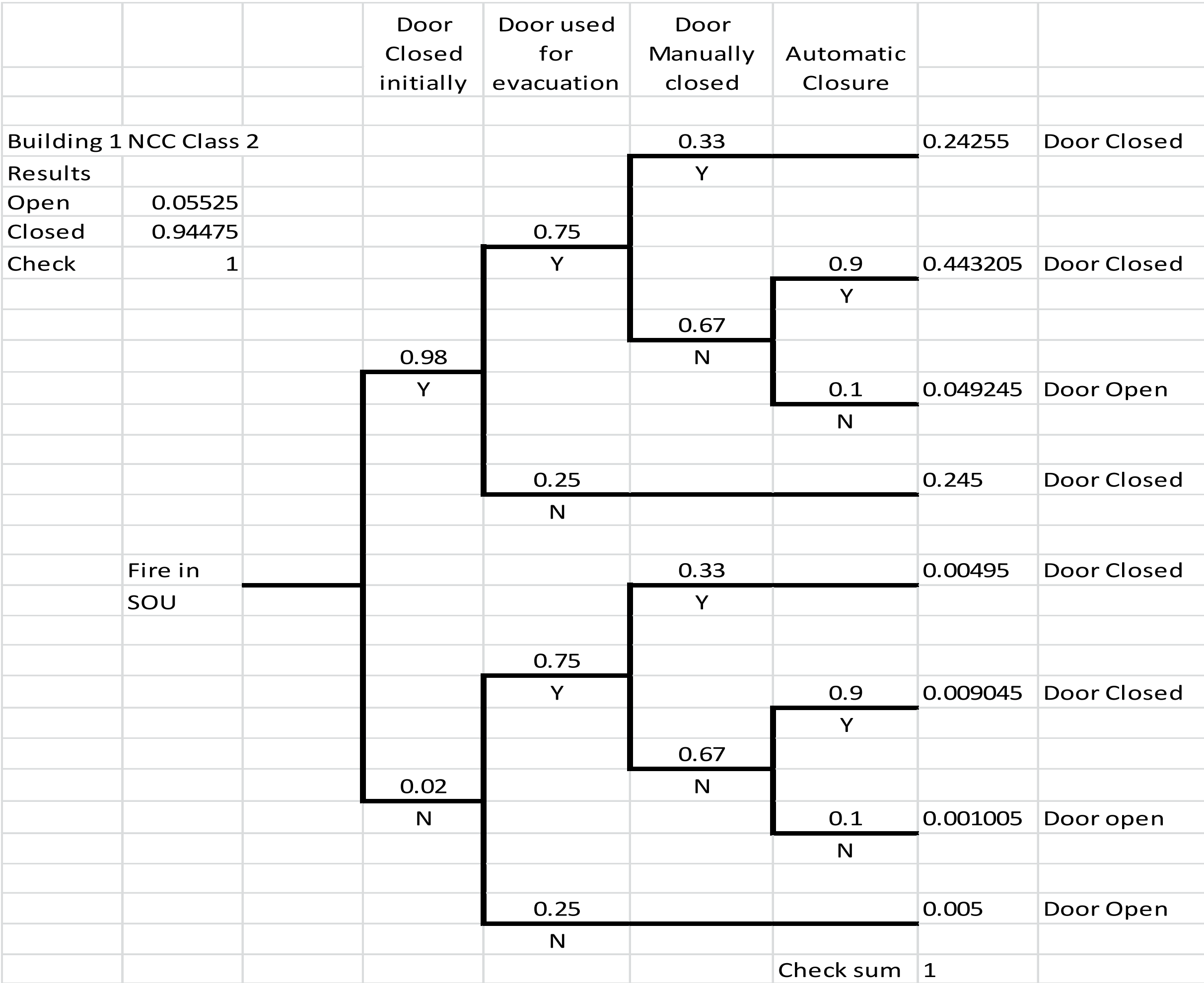
For this example, a value of 0.98 has been assumed that an SOU door will be in the initially closed position.

If the SOU is occupied at the time of a fire and the occupants evacuate the probability of a closed door after evacuation will depend to a large extent on the self-closing function to return the door to the closed position. An approximate estimate of the probability of the SOU being initially occupied at the start of a fire and the occupants evacuating during the fire can be made based on fire statistics and / or other data relating to the building use. For this example, a value of 0.75 has been assumed.

The occupants may manually close the door as they evacuate if the door does not self-close. For this example, a value of 0.33 has been assumed. The probability of the door *self-closing* would be expected to be similar to doors in general evacuation paths (0.9).

These probabilities can be used as part of an event tree to estimate the probability of the door to an SOU of fire origin being closed during a fire scenario as shown in Figure 1 Event Tree for Status of SOU of Fire Origin Door yielding a probability of the door being closed of approximately 0.945 (94.5%).

Figure 1 Event Tree for Status of SOU of Fire Origin Door



Probability of door closed = 1- (0.049245 + 0.001005 + 0.005) = 0.945.

1.3 The Role of Fire and Smoke Doors

Fire and smoke doors can be used as part of a fire and smoke containment strategy to limit the spread of fire and smoke to adjacent enclosures and / or paths of travel to *exits* for sufficient time to facilitate the safe evacuation of occupants and *fire brigade* intervention.

The doors may be required to resist exposure to a range of conditions for varying durations depending on the fire severity, proximity to a fire and the role of the doors in the building fire safety strategy. The exposure of a door is commonly expressed in terms of exposure to ambient medium and high temperatures as described below for design and specification purposes:

- **Ambient temperature** - 20±10˚C.
- **Medium temperature** - 200±20˚C.
- **High temperature** – temperature representative of a *fully developed fire* (generally the standard heating regime or more severe hydrocarbon heating regime prescribed in AS 1530.4 are adopted for testing systems under standardised conditions [5]).

ISO TR 5925-2 [6] provides commentary relating to the applicability of these conditions and use of test data in a smoke containment strategy providing useful information for the development, analysis and specification of *Performance Solutions* involving smoke containment.

A door may be required to resist the spread of fire and smoke when exposed to one or more of the following conditions:

a) smoke at ambient and medium temperatures;
    - during the early stages of a fire scenario
    - when the barrier is distant from the fire
    - a sprinkler-controlled fire

b) smoke at high temperatures;
    - during the *fully developed fire* / decay stages of a fire scenario for a nominated period to allow for evacuation and/or *fire brigade* intervention
    - the total duration of the *fully developed fire* including the decay phase (to resist the total *burnout* of contents).
    - direct flame contact and / or radiant heat from large flaming fires, travelling fires close to a barrier and from sources external to a building.

1.4 Doors Exposed to Ambient and Medium Temperatures

1.4.1 Derivation of Criteria from NCC DTS Smoke Doors

Specification C3.4 of the NCC states under General Requirements that:

Specification C3.4

Smoke doors must be constructed so that smoke will not pass from one side of the doorway to the other and, if they are glazed, there is minimal danger of a person being injured by accidentally walking into them.

In practice there will tend to be some leakage through an element. Since the FSVM adopts a comparative approach and NCC Specification 3.4 provides a DTS form of construction for smoke doors, it is considered reasonable for leakage criteria to be estimated by comparison with the DTS construction when using the FSVM.

AS 6905 [3] specifies the following leakage performance for smoke doors:

(a) Single leaf smoke doors—40 m^3/h at medium temperature conditions (25 m^3/h corrected to Standard Reference Conditions), at a pressure differential of 25 Pa after exposure at 200°C for at least 30 min when subjected to a test in accordance with AS 1530.7 [7].
(b) Two leaf smoke doors—65 m^3/h at medium temperature conditions (40 m^3/h corrected to Standard Reference Conditions), at a pressure differential of 25 Pa after exposure at 200°C for at least 30 min when subjected to a test in accordance with AS 1530.7.

The smoke doors are required to be tested opening towards and away from the heated enclosure unless the direction of exposure can be clearly identified in which case the results from testing with the required exposure apply. The standard notes that:

- incompatible door and seal combinations may result in higher leakage rates when subjected to the AS 1530.7 [7] test
- leakage rates lower than or equal to the above values are achievable and may be specified as part of a *Performance Solution* to satisfy the *Performance Requirements* of the NCC.

Subject to agreement with the PBDB stakeholders the requirements of AS 6905 may be considered as an appropriate benchmark for the performance of a smoke door that is equivalent to the DTS construction pending quantification of the required performance.

1.4.2 Quantification of the Performance of Doors and Derivation of Efficacy

AS 1530.7 [7] provides a method for measuring the leakage through doorsets exposed to ambient and medium temperatures and is generally the most practical method to derive leakage data for hinged smoke doors, but the method is not suitable for high temperature applications.

There are methods that can be used to calculate the leakage through doors without seals at ambient temperatures, for example the method of Gross and Haberman described in Klote and Milke [8]. Such methods do not take account of the differential movement between a leaf and frame that occur at medium and high temperatures and may tend to yield unconservative results under elevated temperature conditions.

The results of an ambient and medium temperature test performed in accordance with UL 1784-1995 (which is broadly similar to AS 1530.7 except that the period of exposure to 200°C prescribed by AS 1530.7 is likely to be greater) are shown in Table 3. The specimen comprised a single leaf-solid core door 2038 mm x 825 mm x 35 mm thick with a 15 mm door stop mounted in a timber framed partition. Clearances around the top and sides of the door were approximately 3 mm and 6 mm at the sill (if a sill seal was not fitted).

Table 3 Results of Air Leakage Tests on a Solid Core Door Tested to UL 1784-1995, Total Leakage (m^3/hour), England et al [9]

Test Pressure (Pa)	Ambient seal fitted at sill only in swing	Ambient no seals in swing	Medium Elevated Temp no seals inswing*	Medium Elevated Temp no seals inswing**	Ambient no seals out swing	Ambient seal fitted at sill only out swing
12.5	89.8	144.7	107.0	172.7	236.7	166.7
25	132.4	213.6	133.5	215.5	N/A	246.1

Notes:

1. * Calculated at standard temperature and pressure.
2. ** Calculated at 200°C and standard pressure.

3. Higher leakage rates may be obtained when testing to AS 1530.7 which requires exposure to 200°C for an extended period.

The results of tests with seals fitted are sensitive to the door clearances and as a consequence any differential movement between the frame and leaf at elevated temperatures. The differential movement tends to be time dependent at medium temperatures and this is specifically addressed in AS 1530.7 by prescribing the timing of measurements. If tests to other standard are being used as supporting data or evidence of suitability the timing of the measurements should be checked.

Results from a survey undertaken by Kettle in 1981 are reported in England et al [9] and include variations in door clearances which are summarised in Table 4. The standard of installation is considered to be poor based on the number of faults observed as part of the survey, but it provides useful data on the potential distribution of clearances for estimating the efficacy of doorsets with and without seals and highlights the need for door sealing systems that can address a broad range of clearances.

Table 4 Door Clearances from 1981 Survey

Max Clearance (mm)	Percent
1	3.2
2	17.7
3	26.7
4	26
5	14.3
6	6.3
7	3.7
8	1.2
9	0.7
10	0.3

The compatibility of the seals with the door leaf and frame constructions is also critical when estimating the efficacy of a seal and normally test data for a door assembly opening towards and away from the heat should be taken into account because large variations can occur depending on the direction of heating and form of construction of a door.

The efficacy of smoke doors depends on the circumstances of the *design scenario* under consideration and will need to be determined on a case by case basis.

1.5 Doors Exposed to High Temperatures

1.5.1 Quantification of the Performance Using AS 1530.4

1.5.1.1 Overview

The NCC DTS provisions relating to fire doors are similar to many national fire safety codes in that the required performance when exposed to high temperatures is generally expressed in terms of a fire resistance time or rating. The NCC adopts the term *fire resistance level* (FRL) which means the grading periods in minutes determined in accordance with AS 1530.4[5] for the following criteria:

- *structural adequacy*; and
- *integrity*; and
- *insulation*,

and expressed in that order.

A dash means that there is no requirement for that criterion.

For example, FRL - / 60 / 30 is a typical specification of the FRL for a fire door and means there is-

- no requirement for *structural adequacy* since it is a non-loadbearing element
- a 60 minute requirement for an FRL for *integrity*; and
- a 30 minute requirement for an FRL for *insulation*.

A radiant heat flux criterion is also applied to fire doors requiring the radiant heat flux at a distance of 365 mm from the non-fire side not to exceed 10kW/m^2.

A major limitation with the use of FRLs is that the performance of fire doors is normally determined by exposing an element to only the standard heating regime prescribed in AS 1530.4. The performance of a fire door when exposed to other conditions (heating regimes), that may be more representative of the *design scenario* being evaluated, is generally not directly determined. Fire doors may be very sensitive to exposure to different rates of heating and heating conditions.

If a *design scenario* heating regime varies from the standard heating regime (which it will in most cases), it is necessary to convert FRLs to an equivalent scenario time when undertaking a fire engineering analysis. Whilst there are a range of methods that can be adopted for this conversion, this process will introduce an increased level of uncertainty particularly if applied to systems that are sensitive to differing heating conditions which should be considered when estimating the effectiveness of barrier systems. This uncertainty can be reduced if the results from tests using different heating regimes and / or data from natural fire experiments are available and can be used to validate the conversion process for barrier systems.

Reference should be made to Data Sheets B3 and B5 for further information.

In the following discussion the performance of fire barriers will be expressed in terms of FRLs and related AS 1530.4 criteria to evaluate the efficacy of the doors with respect to fire spread. Where the FRLs require conversion to scenario time the uncertainty associated with the conversion should be accounted for during the analysis to the degree necessary. Since a comparative approach is adopted by the FSVM in some circumstances the uncertainty associated with this conversion may be less critical particularly if the same barrier system is used for the proposed *Performance Solution* and *reference building*.

The NCC DTS requirements for fire doors are provided in Specification C3.4 Clause 2 which states:

2. FIRE DOORS

A *required* fire door must—

(a) comply with AS 1905.1; and

(b) not fail by radiation through any glazed part during the period specified for *integrity* in the *required* FRL.

1.5.1.2 Structural Adequacy

Structural adequacy does not apply to fire and smoke doors since they are non-loadbearing.

1.5.1.3 Integrity

Integrity is defined as the ability of an element of construction to resist the passage of flames and hot gases from one space to another when tested in accordance with AS 1530.4.

Performance under the criteria of *integrity* for fire doors as defined by AS 1530.4 is determined if:

- a cotton pad applied over an opening crack or fissure is ignited (includes glowing and flaming)
- the presence of a through gap larger than 150 mm x 6 mm or 25 mm diameter (except at the sill of doors)
- sustained flaming on the surface of the unexposed face (non-fire side) for 10s or longer
- for a hinged door with a latching mechanism, if the mechanism becomes disengaged.

If *combustible* materials including linings are close to the position of an opening crack or fissure, fire spread to the non-fire side could occur at approximately the time of the *integrity* failure when exposed to the standard heating regime. If no combustibles are close to the opening the timing of fire spread could be significantly longer depending upon the extent of the *integrity* failure and specific details of a building. If appropriate, the timing of fire spread could be modified to take account of a specific building design where the outcomes may be critically affected. However, in most circumstances it is conservative to assume the spread of fire occurs at the time of failure under the criteria of *integrity*.

1.5.1.4 Insulation

Insulation is defined as the ability of the surface of an element of construction not exposed to the furnace to maintain a temperature below the following specified limits when tested in accordance with AS 1530.4:

- average temperature of the unexposed face of the specimen exceeds the initial temperature by 140 K or
- maximum temperature at any location on the unexposed face of the test specimen exceeds the initial temperature by more than 180 K.

These are below the temperature of unpiloted ignition of most materials over a short period of time but are measured with the surface of the specimen not exposed to the furnace relatively clear of obstructions allowing convective cooling. If *combustible* materials with insulating properties are in contact with the surface the interface temperature could be higher and therefore the timing of fire spread could be modified.

For most hinged fire door applications *combustible* materials are unlikely to be in contact with or close to a fire door particularly in trafficable areas and therefore the time to failure under the *insulation* criteria will be a poor and conservative indicator of the time to fire spread. This observation is consistent with the NCC requirements which generally prescribe FRLs for *insulation* of a maximum of 30 minutes for fire doors.

1.5.2 Radiation

AS 1530.4 and the NCC apply an additional radiant heat flux criterion if a vision panel or similar glazed area is provided in a fire door limiting the heat flux to 10kW/m^2 at a distance of 365 mm for the period required for the FRL of *integrity*.

This level would not be expected to cause ignition of combustibles stored more than 365 mm from the door.

Measured heat flux values also enable the potential risk to occupants from radiant heat as they pass the fire door to be assessed.

1.5.2.1 Estimating Timing of Fire Spread

In most applications it is reasonable to assume that *combustible* materials will not be stored close to the door and the timing of fire spread can conservatively be estimated as the time the *integrity* or radiation criteria are exceeded.

Since the *integrity* performance in most cases will be sensitive to the clearances around the door leaf the data from Table 4 can be used to provide an indication of distribution of the likely performance (efficacy of the fire door). For example, if a 6 mm clearance around the perimeter of the leaf is expected to initiate a premature failure the efficacy of the fire door would be approximately 88% for a relatively poor installation ignoring the variability of materials and construction of the door assembly.

Material variability will further reduce this efficacy particularly if there is a small margin of safety when measuring efficacy against the prescribed FRL.

To predict the timing and probability of fire spread for a scenario, as noted in Section 1.5.1.1 it is necessary to convert FRLs to an equivalent scenario time and then consider intervention from *automatic* fire suppression systems, sprinkler systems and the fire duration to derive an estimate of the efficacy of the system for that scenario.

1.5.3 Smoke Spread Through Doors Exposed to High Temperatures

The spread of hot gases / smoke through elements of construction is generally not measured directly or indirectly during AS 1530.4 tests except where modifications to the test procedures are implemented to gather additional information.

When undertaking fire engineering analyses to determine the outcomes of a *design scenario* it may be necessary to model the spread of hot gases (for example from a *fully developed fire* in an enclosure to an adjoining corridor providing a path of travel to an *exit*).

This will require substantial engineering judgment if there is no directly applicable data for the specific fire doors supported by reference to technical literature, natural fire test data and data from modified test procedures.

Significant work in this field was undertaken in the late 1990s and 2000s in Australia[9-13] using the standard and hydrocarbon heating regimes of AS 1530.4 to investigate the sensitivity to different heating regimes. An instrumented corridor was fitted to the non-fire side of a wall around a door opening to monitor the spread of heat and smoke during the tests.

A brief overview is provided in Appendix B.

The work highlighted amongst other things that:

- the visibility tenability criteria were exceeded substantially before the temperature tenability criteria in the corridor and also substantially before the FRL criteria for *integrity* and *insulation*.
- Tenability can be maintained for a significantly longer period if the door to the SOU of fire origin remains closed and it is fitted with intumescent hot smoke seals and medium temperature seals although the time to activation of a smoke detector in the corridor will also be delayed.
- Use of zone and CFD models is problematic for modelling smoke spread from one enclosure to another through a closed door with or without smoke seals and could not closely model the experimental results. Therefore, caution needs to be applied when analysing smoke spread through closed doors to ensure the outcomes are not sensitive to the modelling methods and assumptions made. The sensitivity can be offset in many cases if the analysis is comparative as required by the FSVM and the door assembly and sealing arrangements are similar.

A.1 C7 Appendix A Data for Estimating Probability of Fire and Smoke Doors Being Closed

A report on the fire system effectiveness in major buildings in New Zealand[14] included inspection data from university, hospital, and office / retail buildings relating to over 5000 passive fire protection systems including fire doors. The results shown in Table 5 have been extracted from the New Zealand Study.

Table 5 NZ Fire and Smoke Door Survey Results

Issue	Fire Doors-%	Smoke Doors -%	Riser Hatches-%
Wedged / blocked	1.9	1.8	N/A
Painted smoke seals	0.5	0	N/A
Missing smoke seals	4.8	10.3	N/A
Excessive clearance	0	1.8	2.5
Carpet under door	1.4	N/A	N/A
Excessive force to open	0.5	N/A	N/A
Missing closers	1.5	1.5	N/A
Damaged closers	0	0	N/A
Not fully closing	2.9	2.9	N/A
Total	13.5	18.3	2.5

These results are incorporated in Table 6 which also includes data provided from other sources including Moinuddin [15] and England [9].

Table 6 Summary of Fire Door Survey Results

Source	Estimated-Reliability
Guymer and Parry – US Nuclear Industry 1970-80 data	92.6%
BS DD240 General fire doors	70%
BS DD240 *Self-closing* door to protected stairwell	90%
Moinuddin and Thomas Australia survey of 16 buildings	79%
Moinuddin and Thomas Australia smoke door estimate from 6 buildings	>65%
FM study of 1183 swinging fire doors	86%
NZ study fire doors	86%
NZ study smoke doors	82%
Kettle UK Study – single doors (closer able to close door)	66%

Of the 34% of doors with faults in the Kettle study only 4.5% could not be closed by manual means. It should be noted that regular maintenance / inspection as required in most States and Territories in Australia would have been likely to improve the performance considerably. The mean of the above results is approximately 80%.

Frank [16] identified that the major disadvantage of the existing data on door reliability was that it is typically compiled from inspection data which provides a "snapshot" of the position of the door in time but does not provide information on how the position of the door has changed over time. To address this, typical doors in occupied residential buildings were monitored. The doors were within the shared means of escape for the buildings (i.e. SOU doors were not monitored). The results are summarised in Table 7.

Frank noted that the results may have been influenced by the residents' knowledge that the doors were being monitored. Nevertheless, this study is considered to provide the most objective data on the reliability of *self-closing* hinged fire doors maintained to a high standard consistent with full compliance with the relevant requirements of AS 1905.1[2], AS 6905 [3] and maintained and inspected in accordance with AS 1851[4].

Table 7 Results from Door Monitoring Tests Extracted from Frank [16]

Type of building	Number of buildings	Number of door leaves	Mean	Standard Deviation
Hotel/backpackers	6	32	0.90	0.16
Apartment/condo	2	5	0.86	0.30
Boarding house/dorm	2	7	0.85	0.32
Rest home	3	8	0.95	0.05
Total	13	52	0.90	0.19

The sample did not include doors with hold-open devices since the sensor could not determine the reliability of a hold open device.

Frank included reported estimates of the reliability of fire doors as well as fire shutters using Tokyo Fire Department data which indicated that:

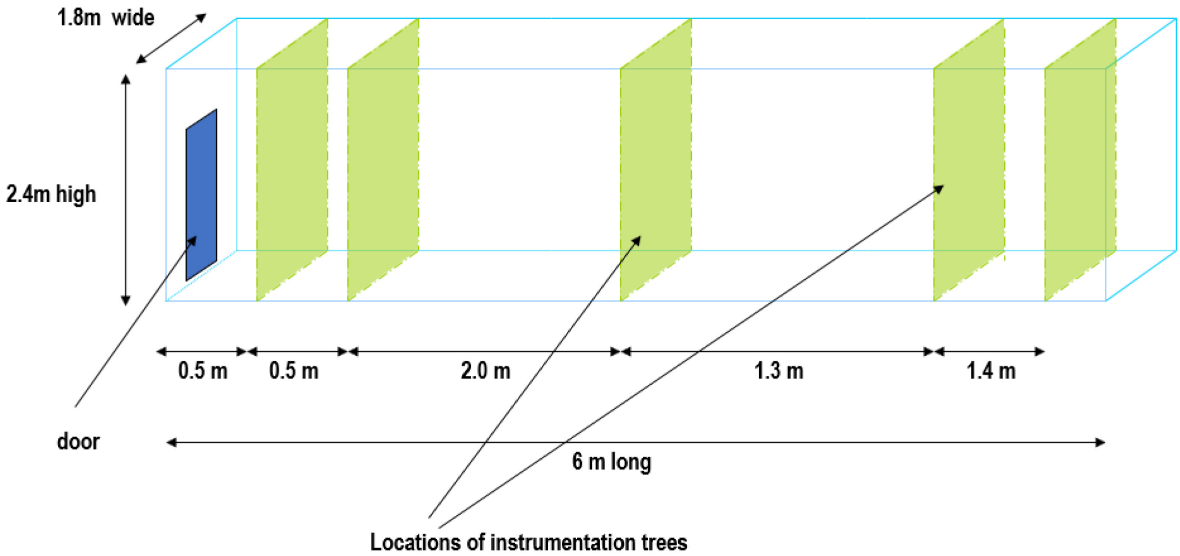
- fire doors with *automatic* closers were estimated to be 97% reliable, and
- fire doors with *automatic* closers and inter-lock were estimated to be 91% reliable.

This indicates that the reliability of an inter-lock (hold open device) would be approximately 94% / unit. It is not clear if this estimate allows for common mode failures of the detection system and therefore it should be assumed that it does not and failure of the doors to close as a result of failure of the detection system should be evaluated as part of a scenario involving failure of the detection system.

A.2 C7 Appendix B Data from Experiments Quantifying Heat and Fire Spread Through Fire Doors.

The following is a brief summary of part of a research program to develop a procedure to determine the spread of fire and smoke through closed doors when exposed to the standard and hydrocarbon heating regimes of AS 1530.4. The test apparatus was configured to simulate a *fully developed fire* occurring on one side of a door and monitor the spread of heat and smoke to a corridor on the other side of the door. The corridor configuration is shown in Figure 2.

Figure 2 Corridor Configuration and Dimensions



A brief summary of the test procedures is presented below:

1. The wall with door frame was constructed, with the door fitted into the door frame. Seals (if required) were fitted to the door assembly. The door leaf was surveyed for gaps around the edges. Thermocouples were installed around the door leaf.

2. The wall with door frame was attached to the furnace opening, the corridor was clamped to the wall frame and sealed using fire mastics and compressed ceramic fibre wool.
3. All thermocouples, smoke detectors, obscuration equipment were connected to the associated data logging equipment and checked.
4. The test was conducted, with the door assembly exposed to the AS 1530.4 standard or hydrocarbon heating regime. Data from all instruments was recorded during the test. The furnace pressure was maintained after the furnace had become stabilised (approximately 2-6 minutes after ignition) such that the pressure at the sill of the door was 0Pa relative to the laboratory. Hence positive pressure was applied to the entire height of the door, but smoke spread at sill level was minimal.
5. The test was continued until the door had burnt through, or a significant opening was apparent.

A summary of the results from a series of four fire tests performed on solid core doors with and without seals and exposed to differing heating regimes is presented in Table 8. The seals included intumescent materials in addition to medium temperature seals to resist the passage of hot smoke. Further details of the test method and results are available in references [9-11].

Table 8 Summary of Test Observations from Solid Core Door Tests Adapted from Young [11]

Parameter	Test 1	Test 2	Test 3	Test 4
Hot smoke seals	Yes	No	Yes	No
Test designation	F91709	F91711	F91715	F91714
Heating regime	Hydrocarbon	Intermediate – Hydrocarbon /Standard	Standard	Standard
Smoke layer commenced forming	6’30”	1’26”	~ 6’00”	~ 4’00”
Smoke layer at approximately 2 m	~11’30” no clearly defined layer	2’11”	no clearly defined layer	~ 5’15”
Very low visibility in corridor	12’30”	3’00”	19’10”	5’45”
No visibility in corridor	13’45”	3’26”	21’30”	6’15”
Flaming on doorlLeaf	12’45”	12’30”	~26’30”	~16’50”

Parameter	Test 1	Test 2	Test 3	Test 4
Exit sign above door not visible	N/A	2’56”	19’00”	5’30”
Time to no visibility after establishment of pressure differential	7’15”	2’00”	15’30	2’15”

Notes:

1. all times are referenced to the furnace ignition time of the tests unless otherwise stated.
2. Test 2 heating regime was between standard and hydrocarbon heating regimes.

Some of the more significant findings are summarised below:

- When no seals were fitted to the doors the smoke passing around the edges of the door entrained air forming plumes diluting the smoke but at the same time increasing the volume of smoke. This tended to accelerate the smoke filling.
- Within approximately two minutes of the establishment of a positive pressure across the doors without seals there was no visibility within the corridor providing limited opportunities for safe evacuation if a rapidly growing fire progresses to *flashover*.
- Smoke spread was substantially reduced in the tests with intumescent and medium temperature smoke seals and a very weak hot layer formed such that the visibility within the corridor slowly reduced throughout the corridor volume. Smoke plumes were not clearly defined on the non-fire side nor was there a clearly defined hot layer. The period between the commencement of smoke filling and there being no visibility was significantly increased to approximately 15 minutes for the standard heating regime and 7 minutes for the more severe hydrocarbon heating regime, significantly increasing the time available for evacuation, but it should be noted that the performance of the smoke seals is dependent upon the seal design and installation and the results cannot be applied to generic seal configurations.
- The time to fire spread as expected varied significantly with the severity of the heating regime.
- Visibility is the critical determinant of tenability in the corridor rather than temperature.

A.3 Appendix C References

1. ABCB, National Construction Code 2019. 2019.

2. Standards Australia, AS 1905.1 Components for the protection of openings in fire-resistant walls Part 1: Fire Resistant doorsets. 2015, Standards Australia: Sydney.

3. Standards Australia, AS 6905 -2007 Smoke Doors. 2007, Standards Australia: Sydney Australia.

4. Standards Australia, AS 1851 2012 Routine service of fire protection systems and equipment. 2012, SAI Global: Sydney.

5. Standards Australia, AS 1530.4 Methods for fire tests on building materials, components and structures Part 4: Fire-resistance tests for elements of construction. 2014, Standards Australia: Sydney.

6. ISO, ISO TR 5925-2 Fire Tests - Smoke -control door and shutter assemblies Part 2: Commentary on test methods and the applicability of test conditions and the use of test data in a smoke containment strategy. 2006, ISO: Switzerland.

7. Standards Australia, AS 1530.7-2007 Methods for fire tests on building materials, components and structures Part 7: Smoke control assemblies—Ambient and medium temperature leakage test procedure. 2007, Standards Australia: Sydney.

8. Klote, J.H. and J.A. Milke, Principles of smoke management. 2002: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

9. England, J., et al., Guide for the design of fire resistant barriers and structures. Building Control Commission, Melbourne, Australia, 2000.

10. England, J. and S. Young, Report of the performance of a solid core timber door in a fire test using a standard heating regime. Warrington Fire Research (Aust) Pvt. Ltd, 1999.

11. Young, S. and J.P. England. The performance of doorsets to restrict the passage of smoke when exposed to simulated fully developed fires. in Interflam 99 Proceedings of the 8th International Conference. 1999. Edinburgh.

12. Chan, K.W., et al., Modelling Smoke Spread to Corridors Through Door Assemblies, in Society of Fire Safety Charting the Course. 2009, Society of Fire Safety: Melbourne.

13. England, J.P., V. Chow, and L. Yunlong, Modelling smoke spread through Barrier Systems, in AIBS Conference 2007. 2007, AIBS: Adelaide.

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Data Sheet C8 General Methods for Conversion of Fire Resistance Times

Group C Data Sheets provide supporting information and guidance relating to the estimation of the effectiveness of fire protection systems and supplement guidance provided in the *Fire Safety Verification Method* introduced into NCC 2019[1] and the FSVM Handbook.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group C Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, C8 describes methods for the conversion of fire resistance exposure times to *design scenario* times to facilitate the estimation of the time dependent performance of elements of construction and building services when exposed to high temperatures. It should be read in conjunction with the FSVM Handbook and other Group B and C Data Sheets which include:

- Data Sheet C1 General overview of the effectiveness of fire protection systems

- Data Sheet C2 Sprinkler System Effectiveness
- Data Sheet C3 Detector Effectiveness
- Data Sheet C4 Active Smoke Control System Effectiveness
- Data Sheet C5 Smoke Barrier Effectiveness
- Data Sheet C6 Fire Barrier Effectiveness
- Data Sheet C7 Smoke and Fire door Effectiveness of hinged doors.

Data Sheet C8 Contents

Version	Date	Data	Comments
C8-1	Jan 2019	C8	Initial draft for comment
C8-2	Jun 2019	C8	Draft for publication

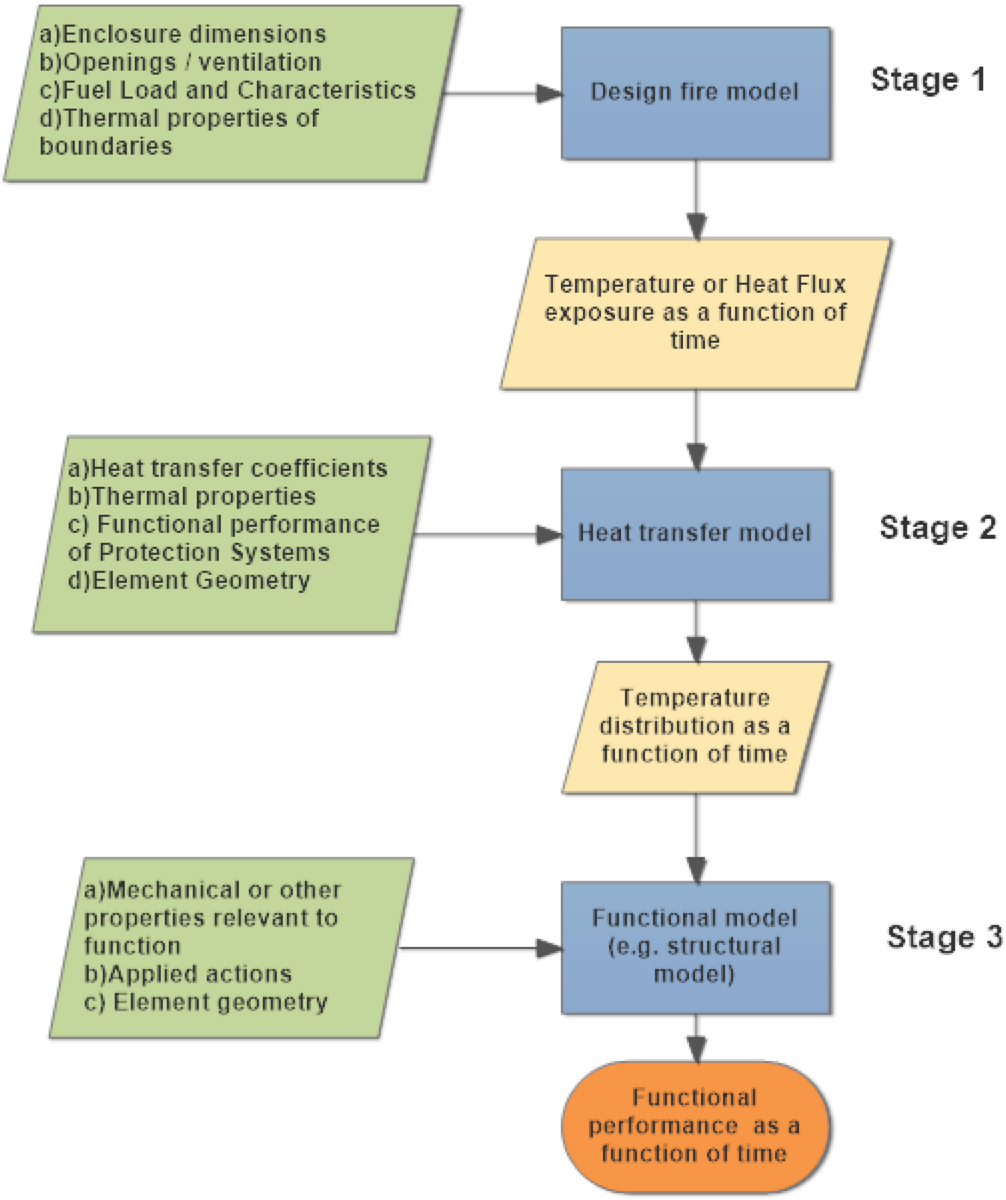
1.1 Introduction

The detailed design of elements of construction and services to resist exposure to a *fully developed fire* typically involves a three-stage process:

- calculation of the fire exposure (Stage 1)
- calculation of the thermal response of the element of construction to the fire exposure (Stage 2)
- calculation of the impact of the thermal response on the ability of an element or structure to perform its design function (Stage 3).

The process is shown in Figure 1 which is a further development of a basic flow chart originally prepared for structural design by Buchanan[2].

Figure 1 Typical Process for Modelling the Performance of Elements of Construction and Services Exposed to Fully Developed Fire Scenarios



Much of the technical literature in this field originates from the design of structures and structural elements to resist exposure to fire but there are a broad range of elements of construction and services which may need to maintain their function when exposed to a *fully developed fire* through all or part of a *design scenario*.

Typical examples include:

- loadbearing structural elements
- loadbearing separating elements

- non-loadbearing wall systems
- fire doors, fire dampers, fire windows, etc.
- service penetrations seals
- fire-resistant cable systems for emergency communications and power.

There are advantages in developing and applying calculation procedures that can address all three stages shown in Figure 1 without reference to standard fire resistance test data (AS 1530.4 [3]) and this may be the case for some structural elements that typically comprise homogeneous materials with known thermal and mechanical properties at elevated temperatures (e.g. steel, concrete, timber). The need for this detailed approach will depend on the specific building design, fire safety features being analysed and methods of analysis.

Many fire-resistant elements or components are too complex to undertake detailed modelling based on material properties at elevated temperatures alone without full scale supporting data. Typical examples include fire doors, penetration seals, composite systems, connections, board fixings, adhesion of sprayed materials, materials prone to spalling, etc.

However, simpler general methods such as those described in this Data Sheet may provide acceptable outcomes particularly if comparative approaches are adopted.

Standard fire resistance tests such as AS 1530.4 provide a practical and established method of providing data under a specific heating regime but the limitations of a single test method using standardised exposure conditions are well known and need to be taken account of when applying the results to *design scenarios* with varying fire exposures. Refer to Data Sheet B3 for further discussion.

It is possible to consolidate some or all the above calculation stages depending on the application under consideration.

For example, the time equivalence concept can consolidate all three stages by relating the expected real fire exposure to a time of exposure under the standard (AS 1530.4) heating regime. Using this approach, the fire exposure (or fire severity) can be expressed as a single equivalent fire resistance test time assuming all the *fire load* has been consumed. The fire resistance of the element is then compared to the equivalent fire resistance exposure time to determine if the element or service is likely to satisfy its design function throughout the fire scenario. Refer to Data Sheet B3 for further information. A major limitation of this approach is that if an element does not withstand exposure for the full duration of the fire, the timing of failure is not determined and therefore the impact of various interventions and evacuation times cannot be compared with the time to failure.

This Data Sheet provides guidance on the use of methods for the conversion of fire resistance exposure times to *design scenario* times to facilitate the estimation of the time dependent performance of elements of construction and building services when exposed to high temperatures addressing one of the major limitations of the time equivalence approach.

The methods effectively consolidate Stages 2 and 3 assuming that the elements of construction under consideration will behave in a similar manner to variations in the heating conditions (as is the case for the time equivalence approach). The output is the time the functional performance of an element or service will be maintained during a *design scenario* based on a conversion of the time to failure under different exposure conditions.

It is necessary to derive the enclosure conditions (Stage 1 in Figure 1) which are used as an input to the conversion process. Data Sheet B3 describes a typical empirical method for deriving the exposure of elements in terms of enclosure temperatures during the fully developed and decay phases of a *design fire* based on parametric curves which may be appropriate under some circumstances.

1.2 Methods for Conversion of Fire Resistance Times

1.2.1 Typical General Methods

There are various options for conversion of fire resistance times. A review of the relationship between fire severity and time-equivalence was undertaken by Wade[4].Time equivalence based on the maximum temperature of protected steel was not considered in detail in the Wade study on the basis that equivalency could only be ascertained if maximum temperatures are achieved. The review recommended the use of an energy based time-equivalent approach as a general method to assess the performance of building elements exposed to compartment fires of different severities based on Kodur's equivalent absorbed energy Method[5].

As an alternative to equivalent absorbed energy methods, it is possible to modify the time equivalence approach so that it can be applied over a range of temperatures. This can be achieved by defining a "target element of construction" with known thermal properties and calculating the temperature at a critical point when exposed to the fire scenarios and the standard heating regime. Equivalent exposure is deemed to have occurred when the element or critical part of the element reaches the same temperature under the different heating regimes. This approach has much in common with the methods used to derive time equivalence relationships for total *burnout* of *fire compartments* with the advantage of being able to calculate failure times prior to a peak temperature being achieved. A typical implementation was described by England [6] and details of the approach are summarised in the following section.

1.2.2 Target Element Method for Conversion of Fire Resistance Times

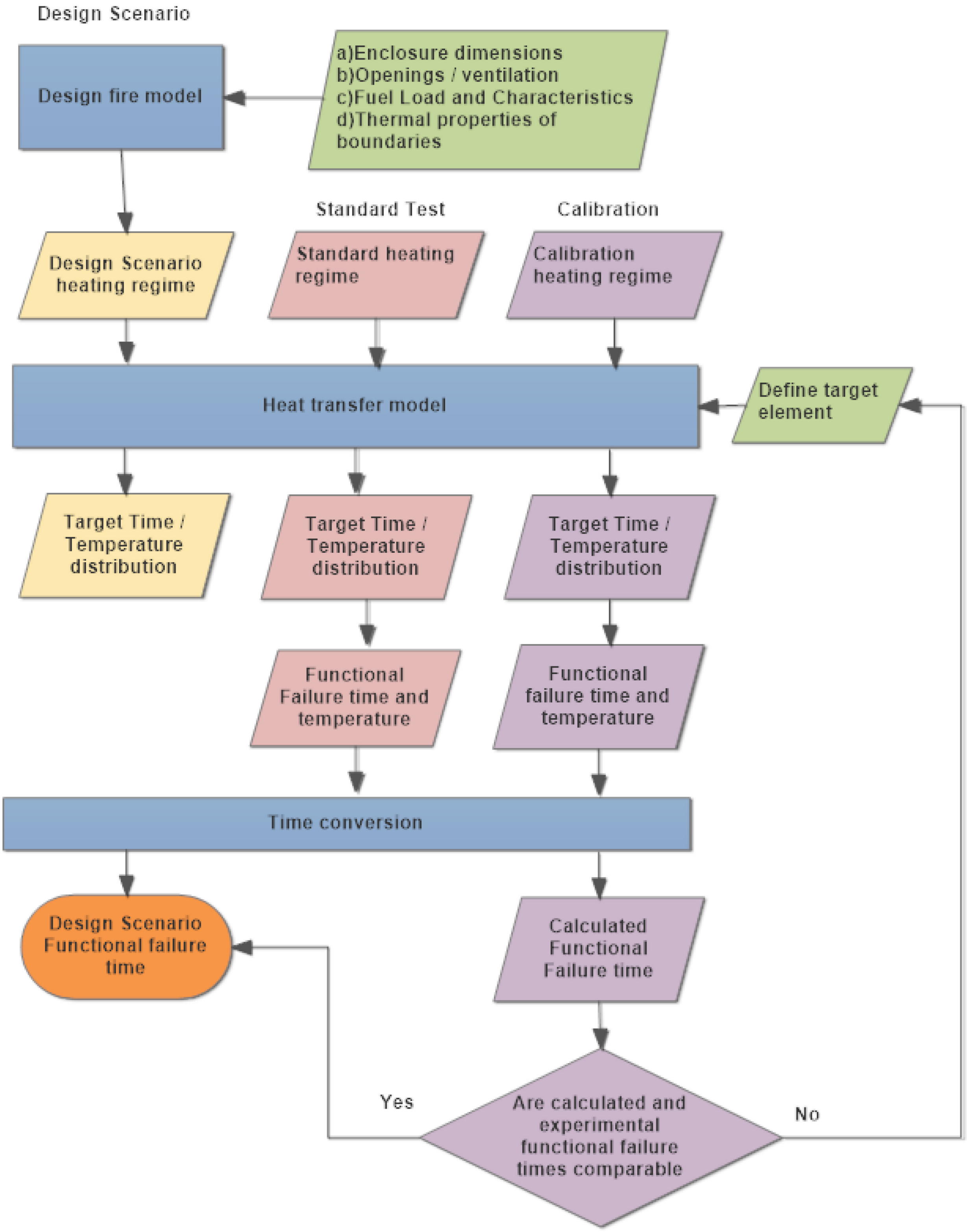
1.2.2.1 Overview of the Method

A schematic of the typical processes to be followed to apply the target element method for conversion of fire resistance times is shown in Figure 2 including a calibration process for comparison with experimental results from different heating regimes if there is available data. The various processes are described in the following sub-sections.

1.2.2.2 Derivation of Design Scenario Heating Regime

The exposure of the element of construction or service is derived using a *design fire* model typically in terms of a time-temperature or time-heat flux heating regime. Refer to Data Sheet B3 for appropriate methods.

Figure 2 Overview of Target Element Method



1.2.2.3 Define a Target Element

A target element should be selected that is appropriate for the heating regimes and expected behaviour of the element of construction or service to be compared and for which there is a heat transfer model that can be adopted for the comparison.

In some cases, the target element and heat transfer model may be directly relevant to the element under consideration but in other situations a more generic target may be appropriate. A protected steel member has been found to be a useful generic target member since the mass of steel and insulation thickness and material properties can be selected to reflect critical features of an element of construction and different durations of exposure.

1.2.2.4 Heat Transfer Model

The heat transfer model should be selected based on the needs of the project. A useful heat transfer model for an insulated steel element that can be readily incorporated into a spread sheet by adopting a lumped thermal mass approach is shown in Equation C8.1 from Milke[7].

$$\Delta T_s = \frac{k_i}{h}\left[\frac{(T_f - T_s)}{c_s(W/D) + \frac{c_i \rho_i h}{2}}\right]\Delta t \qquad \text{Equation C8.1}$$

Where:

T_s is the steel temperature - °C

T_f is the enclosure temperature - °C

k_i is the thermal conductivity of the insulation - W/m.K

c_i is the heat capacity of the insulation – K/kg.K

ρ_i is the density of the insulation – kg/m^3

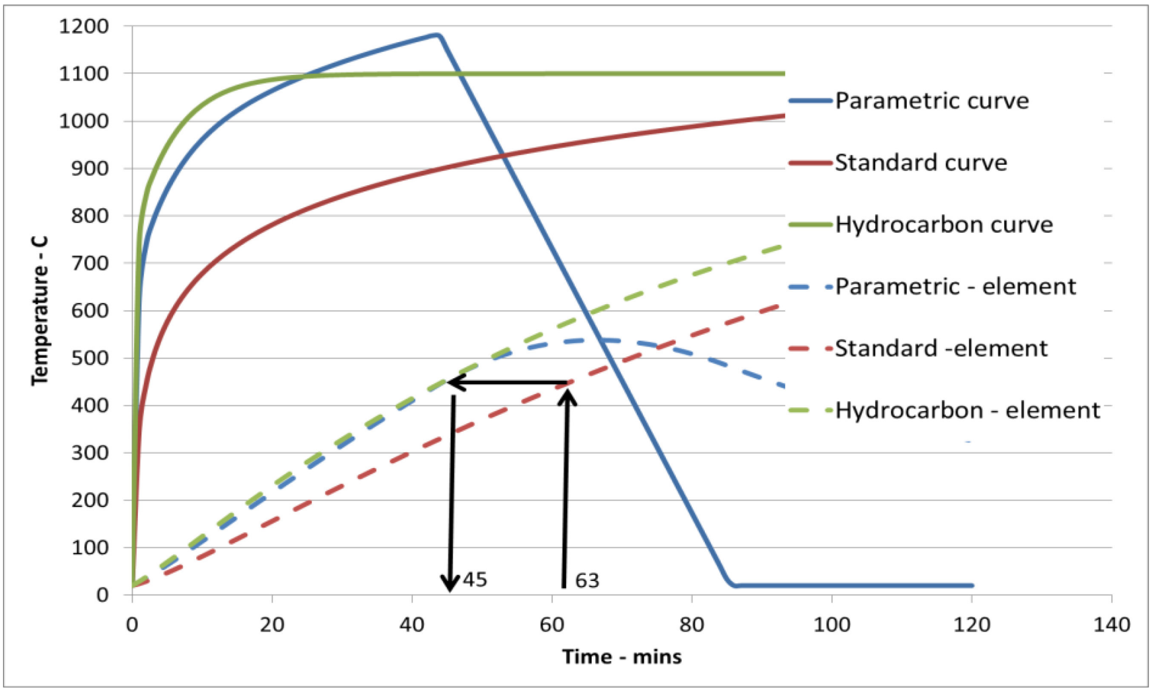
c_s is the heat capacity of steel – J/kg.K

W/D is the mass per unit length divided by the heated perimeter - kg/m^2

Δt is the time step – s.

The time temperature history can be calculated at a critical point based on exposure to the *design scenario* heating regime and the standard heating regime. Data from fire resistance tests using alternative heating regimes (e.g. the hydrocarbon heating regimes) or from reference tests (e.g. natural fire tests) can be used to “calibrate” the conversion process. An example of the process is shown graphically in Figure 3 with supplementary data, based on exposure to the alternative hydrocarbon heating regime from AS 1530.4 used to calibrate the temperature conversion process.

Figure 3 Conversion of Fire Resistance Period to Fire Scenario Time



1.2.2.5 Time Conversion Process

The time conversion process can be simply demonstrated graphically from inspection of Figure 3.

If it is required to determine the functional failure time for an element or service that achieved an FRL of 63/-/- (note; for this example actual failure time has been used rather than values rounded down to the nearest 30 minute FRL increment) when exposed to the *design scenario* (parametric curve) fire the following approach is adopted:

- the target element attains a temperature of 454°C when exposed to the standard fire resistance test for 63 minutes
- the target element would need to be exposed to the *design scenario* (parametric curve) for 45 minutes to attain the same temperature
- hence, the *design scenario* failure time would be 45 minutes.

1.2.2.6 Calibration

The main limitation with the above method is that it considers thermal performance only and does not directly consider the impact of factors such as thermally induced deflections and / or stresses, degradation of structural materials and materials used for protection (e.g. spalling, shrinkage, thermal shock, and critical chemical reactions).

Since the FSVM is a comparative study where the general forms of construction considered in the analysis are not considered particularly sensitive to heating rate this limitation may be considered acceptable subject to agreement of the PBDB stakeholders.

Where practical, to provide additional confidence in the results, the conversion can be calibrated against results from *Standard Fire Tests* or reference natural fire tests with different heating regimes.

In the example, the *design scenario design fire* yields a parametric curve that is closely aligned with the hydrocarbon heating regime. If data from a hydrocarbon fire test on the same element of construction indicated a functional failure time of approximately 45 minutes, it would provide confidence in the application of the conversion method for time temperature regimes which are enclosed by the standard and hydrocarbon heating regimes.

Where this is not the case, the conversion method may not be valid. This could be due to the elements sensitivity to variations in heating rate or the target element may not be representative of the element behaviour. There is a process shown in the flow chart to modify the target such that it is more representative.

Further confidence may be obtained if there are test replicates or tests covering a range of heating regimes, but this type of data is not always available. If supporting data is limited, engineering judgement will need to be employed based on fire test experience, knowledge of material properties and availability of data on similar elements in technical literature and sensitivity analysis may be undertaken. Where results are found to be sensitive it may be necessary to conduct reference tests or apply increased margins of safety.

1.3 References

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2. Buchanan, A.H. and A.K. Abu, Structural design for fire safety. 2017: John Wiley & Sons.

3. Standards Australia, AS 1530.4 Methods for fire tests on building materials, components and structures Part 4: Fire-resistance tests for elements of construction. 2014, Standards Australia: Sydney.

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5. Kodur, V., P. Pakala, and M. Dwaikat, Energy based time equivalent approach for evaluating fire resistance of reinforced concrete beams. Fire Safety Journal, 2010. 45(4): p. 211-220.

6. England, J.P., A Framework for a Risk Based Approach to the Fire Engineering Design of Structures, in 10th International Conference on Performance-Based Codes and Fire Safety Design Methods. 2014, SFPE: Gold Coast Australia.

7. Milke, J.A., Analytical methods for determining fire resistance of steel members, in SFPE handbook of fire protection engineering. 2016, Springer. p. 1909-1948.

GROUP D

DATA SHEETS

Data Sheet D1

Group D Data Sheets provide supporting information and guidance relating to the estimation of occupant response and evacuation during a *design scenario* and supplement guidance provided in the *Fire Safety Verification Method* introduced into NCC 2019[1] and the FSVM Handbook. As such the focus is occupant behaviours relating to evacuation or other avoidance actions taken to avoid harm during a fire emergency such as remaining in a safer place or relocation to a safer place.

Actions relating to matters such as fire prevention, manual suppression, leaving doors open or closed and taking other actions that influence the operation of other fire protection measures are not addressed in the Group D Data Sheets but guidance is provided within the FSVM Handbook and referenced documents.

The FSVM applies a comparative assessment method whereby a *reference building* in full compliance with the NCC DTS provisions is compared with the proposed *Performance Solution* rather than adopting an absolute assessment method. The comparative approach can reduce the sensitivity of an analysis to the selection of design inputs and methods of analysis because in many instances the assumptions and approximations will be the same or similar for the analysis of the *Performance Solution* and *reference building*. This is particularly relevant to occupant response which can vary significantly between individual occupants.

The designers, reviewers and the *appropriate authority* for each project should satisfy themselves as to the suitability of the methods and inputs for a particular application and if necessary, adjust them accordingly. The justification for use of the inputs should be included in the PBDB.

Additional caution should be applied if any content of this Data Sheet is applied to an absolute analysis.

Use of information from Group D Data Sheets is not mandatory and users should determine the suitability for a particular application.

This Data Sheet, D1, provides information relating to:

- calculation of the *required safe egress time* (RSET) concept
- evacuation management strategies
- occupant characterisation
- pre-movement times
- travel times
- evacuation and response models.

Information relating to the above has been consolidated into a single Data Sheet to avoid the need for extensive cross referencing between documents.

This Data Sheet should be read in conjunction with the FSVM Handbook and other Data Sheets relating to the FSVM.

Data Sheet D1 Contents

Version	Date	Data	Comments
D1-1	Feb 2019	D1	Initial draft for comment
D1-2	Jun 2019	D1	Draft for publication

1.1 Calculation of the Required Safe Egress Time (RSET)

1.1.1 Overview

When using the FSVM, if an *available safe egress time* (ASET) v *required safe egress time* (RSET) or similar method of analysis is undertaken to compare outcomes for scenarios the margin of safety (ASET – RSET) for the proposed *Performance Solution* should be greater than or equal to the *reference building* case.

The ASET is normally determined by modelling fire and smoke development and spread and applying the prescribed tenability conditions.

The RSET is determined through the analysis of occupant recognition of, and response to, fire cues and the time to travel to a safe location which requires consideration of human behaviour and other occupant characteristics as modified by an evacuation management strategy where appropriate.

This Data Sheet relates to the determination of RSET values.

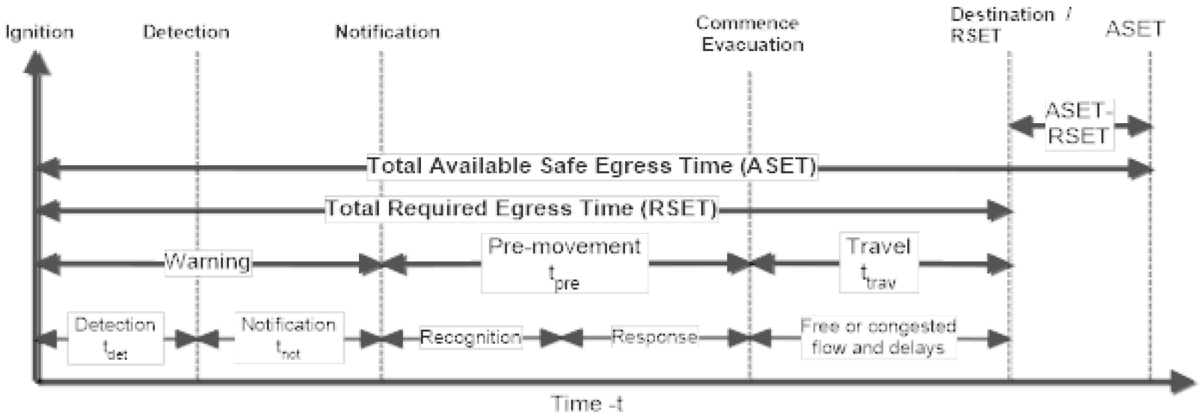
Figure 1 shows a typical graphical representation of a timeline for the determination of the ASET - RSET margin for a typical scenario highlighting the influence human behaviour and other occupant characteristics can have on the magnitude of RSET. In many instances it will be necessary to evaluate several scenarios to account for the diversity in the potential response of occupant groups and individuals as modified by an evacuation management strategy.

The approach shown in Figure 1 and described below for the development of scenarios incorporating aspects of human behaviour is similar to the approaches described in the following publications with minor variations in terminology and reference should be made to these publications for further information:

- ISO / TR 16738:2009 Fire Safety Engineering - Technical information on methods for evaluating behaviour and movement of people [2]
- ISO/TS 29761:2015 — Fire safety engineering — Selection of design occupant behavioural scenarios [3]
- SFPE Guide to Human Behaviour in Fire 2nd Edition [4]

- SFPE Handbook 2015 Chapter 57 Selecting scenarios for deterministic fire safety engineering analysis: life safety for occupants Nilsson and Fahy [5].

Figure 1 Typical Timeline for the Determination of the ASET-RSET Margin of Safety.



RSET can be expressed as the time available between ignition and the time when all the occupants in the specified room, location, and other affected spaces have left that room, location, and other affected spaces and can be represented as:

$$RSET = t_{det} + t_{not} + t_{pre} + t_{trav}$$ Equation D1.1

where:

t_{det} = detection time determined from fire modelling

t_{not} = time from detection to notification of the occupants

t_{pre} = time from notification until evacuation begins

t_{trav} =time spent travelling towards a place of safety including allowances for reduced speed due to congestion and other delays.

1.1.2 Detection Time (tdet)

For *automatic* detection systems the time to detection will normally be estimated by hand calculation or fire models in conjunction with appropriate detector response models. Useful guidance on simple methods for modelling detector response is provided in NFPA 72 Appendix B [6] and Schifiliti et al[7].

In some cases, a detection system may not be provided in a building or the *design scenario* assumes failure of a detection / alarm system. When evaluating these scenarios, it will be necessary to consider other cues with the potential to alert occupants such as auditory, olfactory and visual cues directly from the fire. Where the occupants are more remote, cues from other occupants raising the alarm, *fire brigade* sirens or breaking glass are more relevant.

The timing of these cues can be determined, for example, on the basis of a critical flame height, smoke layer depth, estimated time to window breakage and or *flashover* or *fire brigade* arrival depending on the proximity of the occupants to a fire. The criteria should be agreed as part of the PBDB and generally the same criteria should apply to the analysis undertaken for the *reference building* and proposed *Performance Solution* unless there are differences in the building configurations and fire safety measures that can justify differing criteria.

1.1.3 Notification Time

The notification time is the time between detection occurring and an alarm being raised. For *automatic* systems that activate an alarm immediately, any minor delay is generally small and a nominal allowance of 30s may be considered reasonable for comparative studies such as those required by the FSVM.

Some detection and alarm systems incorporate a delay to allow for alarm investigation and verification and these delays must be included in the notification time since they can have a significant impact on the RSET.

For larger buildings where phased evacuation procedures apply the timing of the alarm may be delayed to certain areas and these delays need to be included in an analysis.

To facilitate an efficient evacuation where phased evacuation approaches are adopted alarm systems commonly have two types of emergency tones:

- Alert tone: which means prepare for an evacuation. Typical emergency procedures for a work place may require occupants to turn off equipment, pack up any personal valuables and await further instructions from wardens, security or speaker announcements.

- Evacuation tone: which means evacuate the building immediately.

Further guidance is provided in Section 1.2.

If there is no *automatic* detection / alarm system or a detection / alarm failure is included in the scenario, then the alarm is needed to be raised by occupants and the following two cases may need to be considered:

- For occupants in close proximity to the fire they may be alerted directly by the occupant(s) that first detected the fire. In this case an allowance in the notification time should be made for cue recognition and response by the occupant discovering the fire and raising the alarm.
- For occupants more distant from the fire the notification time should include a delay to allow for the initial cue recognition and response, plus subsequent delays to allow for reporting via the emergency management reporting chain until a general alarm is raised or until they receive more general cues such as arrival of the *fire brigade*.

1.1.4 Pre-Travel Time

One of the most important factors to consider is the pre-travel time. The pre-travel time is the time between a warning of a fire being given and the time at which the first move is made by the occupant towards an *exit* and is the sum of the recognition time and response time which are described in the following sub-sections.

Both the recognition times and response times that make up the pre-travel time can vary substantially depending on the nature and state of occupants, such as alertness, familiarity, group affiliations, physical and mental conditions, etc. Therefore, within the population of a building the pre-travel times are best represented by a distribution or by a number of Design Occupant Profiles (DOPs) rather than a single value. Further details of typical default pre-travel times for consideration by the PBDB team are provided in Section 1.4.

1.1.4.1 Recognition Time

The recognition time is the period after an alarm or cue is evident but before an occupant of a building begins to respond. During this period occupants are assumed to continue with their normal activities such as working, shopping, sitting or sleeping and if they are aware of their surroundings, they will receive and process cues about the developing emergency situation. The recognition time ends when the occupants have accepted that it is necessary to respond.

The occupant characteristics and nature of the alarm or cue will have a significant impact on the response time.

For example, in residential buildings blood alcohol content (BAC) has a significant impact on recognition time and response time and even at relatively low BAC levels (below 0.05) a significant proportion of occupants may not be awaken by smoke alarms as observed by Ball and Bruck [8].

1.1.4.2 Response Time

The response time is the period after occupants recognise the alarms or cues and begin to respond to them but before they begin the travel phase of evacuation or travel to a safer place within the building depending on the fire safety strategy and *design scenario* under consideration.

During this period the occupants are assumed to cease their normal activities and may undertake other activities relating to the emergency before commencing movement to an *exit* or safer place. Typically, these other activities may include:

- investigations to confirm the cue(s) received and the need for further action
- shutting down equipment that could compromise safety and/ or security
- finding friends and family
- fighting the fire
- alerting others
- deciding whether to evacuate or remain in place
- awaiting further instructions.

1.1.5 Travel Time

Travel times can be calculated from the distance to be travelled and the travel speed for an occupant or group of occupants with appropriate allowances for delays that may occur.

The travel time is commonly considered in two stages:

- the travel time to a protected *exit* (e.g. a fire-isolated stair or passageway); and
- the travel time through the protected *exit*.

This travel time may also need to be increased to allow for:

- decision making during the evacuation process
- additional distances to be travelled if the initial choice of *exit* is unusable
- wayfinding difficulties in complex buildings
- the impact of the evacuation management strategy.

For example, if there is a phased evacuation process in a multi-storey building, on floors distant from the fire floor access to the fire-isolated stair may be delayed, giving priority to the occupants of the floor of fire origin. The interaction with the evacuation management strategy is discussed further in Section 1.2.

Travel speeds vary substantially, and some occupants may require assistance to evacuate. These matters should be addressed in the evacuation management strategy and travel speeds adjusted accordingly. Further modifications to travel speeds should be made where appropriate to account for other variables such as:

- the building layout
- congestion
- presence of smoke and heat from the fire.

Further details of typical default travel speeds and adjustments for consideration by the PBDB stakeholders are provided in Section 1.5.

1.2 Evacuation Management Strategies.

1.2.1 Compatibility with Building Fire Safety Features

The scope of the NCC is focussed on the design of buildings and therefore does not include specific requirements for the ongoing management of buildings, regulation of the construction process and subsequent maintenance of systems through the life of the building, since these matters are regulated by the States and Territories.

With respect to fire safety, the NCC content addresses matters such as active fire protection measures, passive fire protection measures and egress provisions, but commissioning and maintenance of fire protection systems and the development and implementation of appropriate evacuation management strategies are not specifically addressed by the NCC.

The NCC DTS provisions have however, tended to be developed to account for typical evacuation management strategies that are expected to be provided in some buildings having regard for the building class, size and usage, amongst other things.

The following are typical examples:

Under the NCC DTS provisions for Class 9a and 9c buildings:

- Patient care areas and wards in Class 9a and 9c buildings are required amongst other things to be sub-divided into smoke compartments not greater than 500m^2 in area (Clause C2.5).
- *Horizontal exits* must have a clear area on the side of the fire wall to which occupants are evacuating, to accommodate the total number of persons served by the *horizontal exit* of not less than 2.5 m^2 per patient / resident in a Class 9a *health-care building* or Class 9c *aged care building*.

The above provisions are consistent with emergency management procedures based on a phased evacuation with staff assistance.

Clause E4.9 of the NCC includes DTS requirements for intercommunication systems that are consistent with a managed, phased evacuation approach with the option of reducing the volume to minimise trauma to occupants in *health-care buildings* where the evacuation process would be expected to be managed by staff.

E4.9 Emergency warning and intercom systems

An emergency warning and intercom system complying where applicable with AS 1670.4 must be installed—

(a) in a building with an effective height of more than 25 m; and

(b) in a Class 3 building having a rise in storeys of more than 2 and used as—

  (i) the residential part of a primary or secondary school; or

  (ii) accommodation for the aged, children or people with a disability; and

(c) in a Class 3 building used as a *residential care building*, except that the system—

  (i) must be arranged to provide a warning for occupants; and

  (ii) in areas used by the residents, may have its alarm adjusted in volume and content to minimise trauma consistent with the type and condition of residents; and

(d) in a Class 9a building having a floor area of more than 1000 m2 or a rise in storeys of more than 2, and the system—

  (i) must be arranged to provide a warning for occupants; and

  (ii) in a *ward area*, may have its alarm adjusted in volume and content to minimise trauma consistent with the type and condition of patients; and

(e) in a Class 9b building—

  (i) used as a school and having a rise in storeys of more than 3; or

  (ii) used as a theatre, public hall, or the like, having a floor area more than 1000 m2 or a rise in storeys of more than 2.

The evacuation management strategy must be specified as part of the fire safety strategy

It is critical that the fire safety strategy description includes clear details of the evacuation management strategy expected to be in place (and expected performance to be achieved by the evacuation strategy during a fire) in addition to the fire protection measures that are intended to facilitate the safe evacuation of occupants.

The reason for specifying the expected performance to be achieved by the evacuation management strategy is to allow for the evolution of the procedures through the life of the building whilst at the same time specifying the minimum performance that is expected to be achieved so that the time required for evacuation is not inadvertently increased above that allowed for in the *fire safety engineering* analysis.

In most instances the evacuation management strategy for the proposed *Performance Solution* and *reference building* are expected to be similar. Where this is not the case the PBDB should clearly explain the reasons for the variation and associated modifications necessary to the fire safety measures if there is an improvement in the evacuation time for the *Performance Solution*.

Alert

Modifications to evacuation management strategies relating to fire safety should not be used in isolation to justify relaxations to the DTS requirements of the NCC when using the FSVM since it is a reasonable expectation that the evacuation management strategy will be optimised for both the *reference building* and *Performance Solution*.

1.2.2 Evacuation Management Strategies and Human Behaviour

An evacuation management strategy supported by regular staff training and emergency drills can have a significant impact on the required time for evacuation of a building, particularly if there is a reliable means of intercommunication. In these situations, the behaviour of occupants will tend to be more uniform and predictable. These arrangements are common in healthcare facilities, most workplaces and larger public buildings.

For relatively simple alarm systems without provision for intercommunication or where only basic evacuation management strategies are in place together with a relatively informal emergency management organisation, the variability of human behaviour will have a much greater influence on the required evacuation time. These arrangements are common in small to medium size multi-residential buildings, for example.

The modelling of evacuation of the occupants of a building therefore needs to account for the evacuation management strategy that is expected to be in place when applying the FSVM. As part of the robustness check *design scenario*, scenarios involving failure of *automatic* alarms and / or intercommunication systems also need to be considered.

Alert

The fire safety strategy should clearly define how the evacuation management strategy addresses situations where there is a failure of the alarm and / or intercommunication systems and analysis should be undertaken to compare the outcomes for the *reference building* and proposed *Performance Solutions*.

The effectiveness of evacuation management strategies that adopt a phased evacuation approach may also be sensitive to rapid fire spread to multiple floors via the façade of a building. This fire scenario may require evaluation depending on the specific building features and the evacuation management strategy should describe procedures that should be adopted when a fire spreads rapidly to multiple floors.

1.2.3 Applicability of Evacuation Management Strategies to All Occupants

The occupant characteristics for the population within a building are likely to vary substantially in many cases reflecting the diversity within the general population of Australia. The fire safety strategy must identify how the safety of all occupants will be addressed during a fire emergency which will generally be by a combination of physical fire safety features and evacuation management procedures.

1.3 Occupant Characterisation

1.3.1 Overview of Occupant Characteristics

Occupant characteristics can have a significant impact on both the pre-travel and travel times and the vulnerability of occupants exposed to heat and / or smoke from a fire. Important occupant characteristics that should be considered include those listed in Table 9 and relevant building characteristics that influence the ability of occupants to evacuate safely are listed in Table 2. These have been assigned to groups depending on how they will be characterised and subsequently quantified. The descriptions for Groups A and B are based on content from Appendix D of ISO/ TR 16738:2009[2] but have been modified and expanded to include additional criteria that may impact on pre-movement and travel times.

There are a number of other sources that provide similar summaries of critical occupant characteristics adopting slightly different terminology and groups in some cases but providing useful background information including:

- ISO / TR 16738:2009 Fire Safety Engineering - Technical information on methods for evaluating behaviour and movement of people [2]
- SFPE Guide to Human Behaviour in Fire 2nd Edition [4]
- SFPE Handbook 2015 Chapter 57 Selecting scenarios for deterministic fire safety engineering analysis: life safety for occupants Nilsson and Fahy [5].

Abilities of occupants to recognise cues and alarms, respond and evacuate vary from one occupant to the next and can be represented as a distribution but it may be possible to rationalise the distribution into a number of design occupant profiles (DOP).

Each DOP represents occupants of a building that will recognise and respond to cues in a similar manner and time and evacuate at a similar speed. The building population can be assigned to these profiles in proportion to the numbers likely to be present during the *design scenario*.

The final DOPs may not include all the groupings mentioned in the following sections depending on the classification and use of the building.

Table 9 Typical Occupant Characteristics for Consideration When Determining the Required Safe Evacuation Time

Group	Characteristic	Qualitative Parameters
A	Occupant numbers and densities	Expected numbers in each occupied space – typically maximum numbers are assumed for deterministic analyses but variations with times and seasons can be included in probabilistic analyses
A	Activities	Asleep, awake, awareness of surroundings, commitment to activity including responsibilities for activities in an emergency.
A	Familiarity with the building and location	Transitory or long-term. Significance depends on occupancy type, building complexity, induction procedures, signage, proximity to escape routes, etc.
B	Emergency management organisation	Staff / occupant training and participation in drills. XM1 typically long-term occupants are trained to a high level with a comprehensive emergency management organisation with floor wardens and regular fire drills and training. XM2 typically similar to M1 but with lower staff ratio and floor wardens might not always be present. XM3 typically represents a minimal emergency management organisation that commonly applies to small-mid-rise residential buildings with no or limited permanent staff. Reliance on managing the evacuation will tend to fall on the responding *fire brigade*. Note: Some occupants may have specific roles during an emergency such as shut down of plant or a floor warden, etc.

Group	Characteristic	Qualitative Parameters
C	Age	See following characteristics that may be influenced by age.
C	Mobility	Depends on age, temporary injury, physical disabilities.
C	Hearing	Depends on age, temporary impairment, physical disabilities.
C	Vision	Depends on age, temporary impairment, physical disabilities.
C	Mental abilities	Mental illness, intellectual disabilities, age (young and old) and cognitive disorders.
C	Level of intoxication	Alcohol consumption and prescription / non-prescription drugs.
D	Variations to occupant capabilities during a fire	Occupant characteristics may be modified due to exposure to heat of fire effluents affecting decision making and travel speeds as the result of injury or due to fatigue.
E	Social groupings	Is occupant part of a group (family, friends, colleagues)? Is a member of a group in another part of the building?
E	Emotional attachment to objects and animals	Occupant commitment to saving companion animals or critical objects / possessions. May increase response time whilst possessions and animals are gathered, or occupants may return to a more hazardous location.

Table 10 Typical Building Characteristics for Consideration When Determining the Required Safe Evacuation Time

Group	Characteristic	Qualitative Parameters
A	Compartment complexity	Number and configuration of enclosures within a compartment / functional area.
B	Building complexity	XB1 typically simple building with few enclosures. XB2 typically simple multi-storey buildings e.g. offices. XB3 typically large complex buildings with poor building legibility.
B	Alarm system	XA1: *automatic* detection throughout the building activating an immediate general alarm to occupants of all affected parts of the building. XA2(a): (two stage) *automatic* detection throughout the building providing a pre-notification to management or security with a manually activated general warning system sounding throughout affected occupied areas and

Group	Characteristic	Qualitative Parameters
		a general alarm after a fixed delay if the pre-alarm is not cancelled. XA2(b) two stage alarm with prepare to evacuate and evacuate tones configured such that upon alarm a prepare to evacuate building wide alarm is activated and evacuation tones sound on the fire floor. The system then cascades through the remaining floors either automatically or manually with priority given to floors closest to the fire floor. XA3: local *automatic* detection and alarm only near the location of the fire or no *automatic* detection with a manually activated general warning system sounding throughout all affected occupied areas. The need for provisions for the hearing impaired should be considered.
C	Egress design	Paths of travel to *exits* and *exit* options (distance, dimensions / capacity, height, availability of *horizontal exits* etc., features that reduce the risk of obstruction etc.). Emergency lighting and back-lit emergency *exit* signage. Provisions for people with limited mobility such as *horizontal exits* / evacuation by lifts, additional circulation space, protected areas, etc.
D	Overall fire safety system design	Control of fire and smoke spread to path of travel to *exits* and to *exits*.

Base behavioural scenario categories have been defined in Section 1.3.3.2 to address the Group A characteristics in Table 9 and Table 10.

Major behavioural modifiers are defined in Section 1.3.3.2 to address the Group B characteristics.

A significant proportion of the population may be slow or unable to recognise, respond or evacuate due to temporary or permanent disabilities, age or other factors such as levels of intoxication. Refer Group C in Table 9.

The ability of occupants to recognise, respond or evacuate promptly can be compromised due to the impact of heat / smoke on the occupants, other injuries sustained during a fire emergency and fatigue (see Table 1 Group D). These modifiers are discussed in Section 1.3.3.4.

Egress design (Group C in Table 10) and other aspects of the fire safety strategy for a building (Group D in Table 10) can be optimised to improve the evacuation efficiency for people with disabilities and reduce the risk of exposure to heat and smoke on paths of travel to *exits*.

Human behaviour during a fire emergency may be modified when an occupant is part of a social group or has strong emotional attachments to objects or companion animals (identified under Group E in Table 9). These modifiers are discussed in more detail in Section 1.3.3.5.

1.3.2 Occupant Numbers and Densities

The occupant numbers (or densities) for the *reference building* and specific areas within the *reference building* should be calculated using the values from NCC Volume One Table D1.13 for the area required per person based on the use of the functional area.

If values are not specified within Table D1.13 for the use of a functional area within the *reference building* the *Appropriate Authority* in conjunction with the fire safety engineer and other PBDB stakeholders should determine a value for the area that is generally consistent with the values stated in D1.13.

Any variations in populations from the *reference building* for a proposed *Performance Solution* must be clearly identified in the PBDB report and the impact of the variations evaluated in the analysis.

Alert

The fire safety strategy must clearly state the maximum number of occupants assumed for the building and enclosures within a building. The NCC default values given in NCC Table D1.13 must be used for the *reference building* where they are relevant to the functional use of a building or part of a building. Any variations in the number of occupants between the *reference building* and proposed *Performance Solution* must be clearly identified in the PBDB.

1.3.3 Design Behavioural Scenarios and Occupancies

1.3.3.1 Base Scenarios

The base behavioural scenario categories identified in Table 11 have been derived from Appendix D of ISO/TR 16738:2009 [2] with minor adjustments for application with the FSVM.

Table 11 Base Scenarios from Appendix D of ISO/TR 16738:2009 With Minor Adjustments for Application in Australia

Cate-gory	Description of occupancy	Occu-pant Density	Occupant Activity	Occupant Familiarity	Compartment Complexity
A	Staff in workplaces High density applies to workplaces with large numbers of visitors	Low – High1	Awake & aware of surroundings	Familiar	Simple to complex
B1	Shop, restaurant, bar- circulation space (visitors)	High	Awake & aware of surroundings	Unfamiliar	Intermediate (variable)
B2	Cinema, theatre (visitors)	High	Awake & aware of surroundings	Unfamiliar	Intermediate (variable)
C1	Apartment -no evac management org	Low	Asleep2	Familiar	Intermediate
C2	Hotel, motel, hostel sleeping areas	Variable	Asleep2	Unfamiliar	Intermediate
D	Residential care buildings and health-care buildings	Low	Asleep2 - some unaware	Familiar - unfamiliar	Complex
E	Transportation	High	Awake & aware of surroundings	Unfamiliar	Complex

Note 1: High occupant density applies to workplaces with large numbers of visitors such as public buildings. Evacuation of visitors is addressed for these buildings under Category B1, B2 and E. In

other workplaces were the number of visitors is significantly below the numbers of staff, a low occupant density should be assumed to derive response and times under Category A.

Note 2: For Categories C1-C2 and D the status of occupants is assumed to be asleep to represent a challenging scenario for verification purposes. For analyses where day time scenarios are considered relevant additional base scenarios will be required which should be derived based on case studies and other technical literature.

1.3.3.2 Major Behavioural Modifiers

For consistency with ISO/TR 16738:2009 Appendix D three major behavioural modifiers are to be applied. The modifiers are described in Sections 1.3.3.2.1 to 1.3.3.2.3.

There is some ambiguity in the designation of categories and modifier identifiers in ISO/TR 16738 and to reduce this ambiguity an X prefix has been added to the reference for each behavioural modifier.

Suggested pre-travel activity times for the scenario categories including adjustments to allow for major behavioural modifiers based on ISO/TR 16738:2009 are provided in Section 1.4 with adjustments for application with the FSVM.

The suggested pre-travel activity times should be used only where there is no more appropriate data and under these circumstances they should be reviewed and agreed by the PBDB stakeholders including any required modifications.

1.3.3.2.1 Emergency Management Organisation

Three levels of emergency management organisation have been identified in Table 9:

XM1: typically long-term occupants are trained to a high level with a comprehensive emergency management organisation with floor wardens, regular fire drills and training.

XM2: typically similar to XM1, but with lower staff ratio and floor wardens might not always be present.

XM3: typically represents a minimal emergency management organisation that commonly applies to small mid-rise residential buildings with no or limited permanent staff. Reliance on managing the evacuation will tend to fall on the responding *fire brigade*.

1.3.3.2.2 Detection / Alarm System

Four levels of detection and alarm system have been identified in Table 10 and are summarised below:

- XA1: *automatic* detection throughout the building activating an immediate general alarm to occupants of all affected parts of the building.
- XA2(a): (two stage) *automatic* detection throughout the building providing a pre-notification to management or security with a manually activated general warning system sounding throughout affected occupied areas and a general alarm after a fixed delay if the pre-alarm is not cancelled.
- XA2(b) two stage alarm with prepare to evacuate and evacuate tones configured such that upon alarm a prepare to evacuate building wide alarm is activated and evacuation tones sound on the fire floor the system then cascades through the remaining floors either automatically or manually with priority given to floors closest to the fire floor.
- XA3: local *automatic* detection and alarm only near the location of the fire or no *automatic* detection with a manually activated general warning system sounding throughout all affected occupied areas.

XA2(b) has been added for consistency with modern systems set up for phased evacuations. On the fire floor a response similar to XA2(a) would be expected but the commencement of evacuation from other floors will be delayed accordingly.

The need for provisions for the hearing impaired should be considered.

1.3.3.2.3 Building Complexity

Three levels of building complexity have been identified in Table 10 and are summarised below:

- XB1: typically simple building with few enclosures.
- XB2: typically simple multi-storey buildings e.g. offices.

- XB3: typically large complex buildings with poor building legibility.

1.3.3.3 Temporary or Permanent Disabilities and Related Modifiers

1.3.3.3.1 Categories of Disabilities

Disabilities can be grouped into five major categories shown in Table 12.

The overall ability of many people as they age will reduce and for more severe cases they will be included in the estimated percentages of people with specific disabilities. Obesity, diseases of the heart or lungs, lack of coordination, arthritis, and rheumatism can reduce a person's physical stamina or cause pain. In addition to people with permanent or long-term disabilities, there are others who have temporary conditions that affect their usual abilities.

Table 12 Disability Categories and % of Australian Population Based on ABS Supplementary Disability Survey, 2016[9]

Activity	Sub groups	Matters for consideration	% Australian population1
Mobility	Wheelchair users	Adequate space for manoeuvring. Avoiding uneven surfaces. Negotiating steps or changes in level. Reaching and seeing items placed at conventional heights.	4.1
Mobility	Ambulatory mobility disabilities	Walking, climbing steps or slopes. Standing for extended periods of time. Reaching, and fine finger manipulation.	N/A
Mobility	Diseases of the heart or lungs and other disabilities	People with diseases of the heart or lungs can generally use the components of the egress system but may have difficulty safely evacuating over a lengthy period of time. Such people may require rest breaks while evacuating.	See below regarding other disabilities
Vision	N/A	Wayfinding. Obstructions.	0.9
Hearing	N/A	Risk of missing an auditory cue and instructions.	1.6

Activity	Sub groups	Matters for consideration	% Australian population1
Cognitive / memory	N/A	Results from a range of causes including developmental disabilities,multiple sclerosis, depression, alcoholism, Alzheimer's disease, Parkinson's disease, traumatic brain injury, chronic fatigue syndrome, stroke. Occupants will have an impaired ability to process or understand information and instructions received.	1.6
Speech	N/A	Main limitation is if a person needs to communicate by emergency phone systems in areas of refuge, elevators, or similar locations.	0.6

Note: % specified applies to people who reported a lot of difficulty or cannot do the activity at all.

1.3.3.3.2 Representative Occupant Profiles for People with Disability

To account for people with all abilities in a practical manner the DOPs shown in Table 13 have been defined to reflect occupants with severe or profound disabilities. The default % of occupants have been based on ABS statistics for the general population and it may therefore be appropriate to apply these percentages to *accessible* buildings and multi-residential buildings where it is reasonable to assume the distribution will be similar to the general population.

Table 13 Representative Design Occupant Profiles for People with Disabilities

Activity	Default %	Cue Recog-nition	Resp-onse	Travel	Notes
Mobility	4	A	B	C (B)	Response delayed in some occupancies (e.g. residential). Reduced travel speeds and increased space required for horizontal travel. Evacuation management strategy should address vertical travel.

Activity	Default %	Cue Recog-nition	Resp-onse	Travel	Notes
Vision	1	B	B	B	No recognition of visual cues. Response delayed in some occupancies (e.g. residential). Wayfinding and negotiating obstructions reduce travel speed.
Hearing	1.5	C (B)	B	B	Risk of missing an auditory cue and instructions. Improvements can be made using visual or physical alarms
Cognitive / memory	1.5	C	C	C	There may be no cue recognition or response and evacuation without assistance. With assistance all times would be increased.
Speech	0.5	A	B	A	Only variance from a standard occupant would occur during the response phase if communication is required. For most evacuation situations this profile would be the same as a person without disabilities.

Key: A = similar to general population DOP, B = adjustment required to DOP for general population, C = assistance or additional measures required for evacuation.

The proportions of occupants with disabilities will vary from the standard population considerably for some occupancies and for the following buildings, patients / residents with disabilities may approach 100% and staff assistance for most patients / residents to evacuate may be required:

- hospitals
- residential care facilities
- aged-care accommodation.

It is therefore necessary to determine if the default distribution is applicable or an alternate distribution needs to be developed for a specific project. The basis for this decision should be documented in the PBDB report and agreed with the relevant stakeholders.

1.3.3.3.3 Level of Intoxication

Levels of intoxication from alcohol consumption and the effects of prescription or non-prescription drugs can have a significant impact on alarm / cue recognition and response times in residential occupancies.

This was explored by Ball and Bruck [8] who found that results from a study on a group of young adults suggested that drinking alcohol, even in moderation, will adversely affect a person's ability to awaken to their smoke alarm.

Key observations included the following:

- regardless of the signal, 36.11% of all trials resulted in no response before 95dBA, or worse still no response at all, at just 0.05 Blood Alcohol Concentration (BAC.) which increased to 41.67% when the BAC was elevated to 0.08
- the international standard for audible emergency evacuation signals requires that the minimum sound intensity level at the bed head should be 75dBA when the signal is being used to awaken sleeping individuals (ISO 8201). The results imply that it is unlikely that the mandated sound level would have aroused one in three participants at 0.05 BAC, and almost half of all participants at 0.08 BAC.

The relevant Australian Standard AS 1670.1 requires that the minimum sound intensity level should also be 75dBA.

An indication of a baseline response without the influence of alcohol or drugs can be obtained from Duncan [10] who carried out experiments in residential settings with a simulated residential alarm placed in the corridor outside bedrooms and determined that in 85% of cases young adult occupants were alerted (15% not responding).

For residential buildings a "no response" occupant profile should be included to address the proportion of occupants that are unlikely to respond to audible alarms and other cues without assistance from other occupants which should account for the probability of occupants with elevated BAC levels and the impact of drugs.

BAC can also have an impact on occupants that are awake at the time of a fire emergency, which is particularly relevant in non-residential buildings where alcohol is available for consumption such as pubs, restaurants and nightclubs and other *assembly buildings* where a large proportion of occupants may be intoxicated.

For example, an experimental study reported by Anderson et al [11] suggests that acute alcohol use impairs cognitive control through a dose-dependent decrease in cortical activation leading to slower responses, amongst other things.

Vorst [12] indicated that alcohol consumption strongly impairs cognitive processes and attention, emotional systems will be over-stimulated, and motor functions will be hampered. For unclear, stressful evacuation circumstances Vorst provided the following estimates of the impact that alcohol consumption could have on the speed and number of casualties based on general psychology:

- Most people (50% or more) are unable to make adequate risk estimations in typical evacuation situations, due to alcohol and stress.
- Most people are not inclined to evacuate. This will cause delayed evacuation and more casualties.
- Most people are unable to make adequate decisions in new problem situations, due to alcohol and stress.
- Most people are unable to communicate (speaking and listening) unambiguously and clearly, due to alcohol and stress.
- Most people tend to focus their attention extremely (tunnel vision), due to alcohol and stress. They do not have the overall picture of new situations needed for optimal adaptive behaviour.
- Most people tend to behave as they do normally. They choose well-known behaviours or copy behaviours from others near them.
- Most people have lowered thresholds of emotional behaviour due to alcohol and stress. They are easily triggered to be angry, anxious or aggressive.
- Most people are unable to control and smoothly perform motor activities due to alcohol and stress. They are prone to accidents.

DOPs should therefore be adopted that account for the above factors for analysis of buildings where there may be significant numbers of intoxicated occupants.

1.3.3.4 Variations to Occupant Capabilities During a Fire

1.3.3.4.1 Exposure to Fire Effluents and Visibility

The ability of occupants to recognise and respond to cues can be influenced by exposure to fire effluents prior to the onset of untenable conditions. Sleeping occupants in residential buildings are most at risk. Accurately quantifying these effects is difficult but since the FSVM adopts a comparative approach if the smoke detection and alarm systems are sufficiently similar for the proposed *Performance Solution* and *reference building* the impact on cue / alarm recognition and response time can be assumed to be addressed by consideration of occupants with a “no response” profile.

Reduced visibility and exposure to heat and fire effluents on paths of travel to *exits* and within *exits* may reduce travel speeds and affect decision making capabilities.

The FSVM adopts a conservative approach to the specification of untenable conditions by adopting a visibility limit of 10 m except in rooms of less than 100 m^2 or where the distance to an *exit* is 5 m or less, where visibility may fall to 5 m in addition to thermal exposure limits.

In most circumstances the visibility criteria will be exceeded substantially before an occupant is exposed to concentrations of fire effluents for a sufficient period to significantly compromise the cognitive processes required of the evacuating occupants. Since the FSVM adopts a comparative approach and the same assumption applies to the analysis of the *reference building* and the proposed *Performance Solution*, it is considered reasonable to apply the following simple approach:

- Generally, it is not necessary to consider delays in the pre-movement times due to exposure to fire effluents. If occupants are asleep any risk of exposure and delayed cue recognition and response will be inherently considered as part of the analysis of the no-response DOP.
- Occupants will move through smoke provided the tenability criteria for visibility have not been exceeded for the relevant enclosure but at a reduced speed (refer Section 1.5 for further details).

- If occupants encounter smoke in an enclosure that exceeds the tenability criteria the occupants will not enter the enclosure and turn back and either attempt to find an alternate *exit* or safer place and await assistance.

1.3.3.5 Impact of Social Groupings and Emotional Attachments

1.3.3.5.1 Social Groupings

Based on a review of previous studies Nilsson and Fahy [5] found that groups of people, and particularly family groups, will tend to assemble before evacuating and will likely move together, at the speed of the slowest member, so the presence of family groups can have an impact on evacuation.

DOPs should therefore be defined for occupancies where family groups and other social groups are present, and these DOPs should allow for:

- extended pre-movement times for assembling the group; and
- slower travel speeds to account for the slowest group member.

In residential occupancies housing a family group or group of friends within a single dwelling or SOU, group affiliation can have a positive impact on the evacuation process since occupants that respond to alarms are likely to awaken other occupants. Under these circumstances the proportion of no-response DOPs should be reduced.

This outcome was observed by Xiong et al [13] whilst undertaking a review of fatal fire incidents. It was found that the risks of dying in accidental residential fires were closely associated with the social environment in which a host resides, particularly living alone or being home alone at the time of a fire and the authors suggested that the presence of multiple active occupants is likely to increase the chance of detecting the presence of fire and the successful implementation of fire plans and coping strategies in exposure to fires.

1.3.3.5.2 Emotional Attachment and Re-entry Behaviours

Particularly in residential buildings, there may be a tendency for occupants to re-enter a building or apartment after evacuating. For example, early results reported by

Wales [14] identified that almost 40% of respondents who evacuated residential properties re-entered at least once and did so in order to undertake specific tasks which included collecting household documents, rescuing pets and closing internal doors.

If appropriate a specific DOP could be set up for this response or it may be possible to address these behaviours in the DOP for a slow evacuation.

1.3.3.5.3 Roles and Perceived Authority

If a building has an effective emergency management organisation in place including appropriately selected and trained fire wardens with regular drills / exercises being performed, the response of occupants can be assumed to be consistent with the evacuation strategy and will be less susceptible to variations in human behaviour if all *fire safety systems* are operational.

As noted by Nilsson and Fahy [5] “It has been observed in real fires that occupants may continue to function in certain roles, particularly those they fill during the normal use of the building; for example, servers in a restaurant assisting the guests at their tables, and the guests looking to the servers for guidance. Similarly, students may look to teachers for guidance, employees may look to managers or supervisors, etc.”

Therefore, if a relatively informal emergency management organisation is in place the evacuation outcomes are likely to be influenced by the actions of occupants with perceived authority and other aspects of human behaviour in fire.

DOPs and modelling of the evacuation process will therefore differ depending upon which of the above *design scenarios* is appropriate. Kuligowski [15] provides a review of human behaviour in fire focussing on fire safety design which provides useful background information.

The FSVM requires a robustness check *design scenario* to be analysed. As part of the robustness check a failure of the alarm / communication systems which could compromise the operation of an evacuation strategy should be considered.

1.3.4 Deriving Evacuation Scenarios and Design Occupant Profiles

When calculating RSET it is necessary to clearly define the evacuation scenario that is under consideration which will generally be derived from one of the *design scenarios* prescribed by the FSVM.

The *design fire* and subsequent fire and smoke modelling needs to be considered since it impacts on the time and quantity of secondary fire cues (or in the case of a robustness check *design scenario* involving failure of a detection / alarm system the primary cue). Smoke spread may also influence the selection of paths of travel and travel speeds and ultimately enables the time to untenable conditions to be determined.

The influence of the emergency management organisation may also be critical. In some occupancies such as hospitals the emergency management organisation and associated evacuation strategy will dominate the evacuation scenario whereas in other occupancies such as apartment buildings the DOPs will be dominant. Section 1.2 provides information on evacuation management strategies and the role of the emergency management organisation.

Quantifying the behaviour of the population of a building during a fire emergency is a difficult task because of the variability in human behaviour and physical and mental capabilities as well as the influence of activities at the time. Ideally this should be represented as a distribution of pre-movement times, travel speeds and decisions made during the evacuation such as selections of *exits*. However, for many analyses such an approach may be impractical, and some simplification is required.

A practical approach is to simplify the distribution to a series of DOPs which can be assigned to individuals or groups of individuals that can be considered to act as a unit and assign these to proportions of the building occupants. The DOP should as a minimum define pre-movement times and travel speeds but may also need to include factors such as selection of path of travel to *exits* and vulnerability to exposure to fire effluents.

The number of DOPs necessary will depend upon the building and occupancy under consideration. For a single dwelling there could be as few as four DOPs to categorise the response on an individual (prompt, slow, medium and no response) and scenarios should be evaluated for each of these DOPs to check that the proposed *Performance Solution* achieves at least equivalent levels of safety to the *reference building*.

People with disabilities, the aged, intoxicated occupants, etc. can be incorporated by adjusting the proportions of slow and no response as appropriate.

For large buildings and populations, substantially more DOPs may need to be developed to adequately reflect the building population.

1.4 Pre-movement Times

1.4.1 Derivation of Pre-movement Times

Pre-movement times can vary largely depending on many of the factors described in the preceding sections and since many of these will vary from one building to the next pre-movement times should be derived on a case-by-case basis drawing on available technical literature, results of evacuation exercises and fire incident reports.

Some useful compilations are provided in:

- ISO/TR16738 Fire Safety Engineering – Technical information on methods for evaluating the behaviour and movement of people [2]
- Gwynne and Boyce; Chapter 64 Engineering Data; SFPE Handbook of Fire Protection Engineering [16].

The following sub-sections provide suggested default values for functional areas within certain occupancies. These values were derived from the base scenarios from Appendix D of ISO/TR 16738:2009. Adjustments were made to introduce prompt, medium, slow and no response pre-movement values including indicative proportions for inclusion in a range of DOPs to provide a crude characterisation of the building population.

Reference should be made to Section 1.3 for further details on category attributes and the various levels of emergency management organisation detection and alarm systems and building complexity.

Alert

The pre-movement times in the following sub-sections provide suggested default values that must be reviewed against available technical literature, results of evacuation exercises and fire incident reports and adjusted as appropriate to better represent the specific building features, occupants and scenarios under consideration. This process should be documented in the PBDB report.

Typical examples of adjustments that should be considered on a case by case basis are:

- The three-point characterisation of response times as slow, medium and prompt for input into DOPs may be too crude presenting unrealistic outcomes if 80% of occupants commence movement at the same time. The characterisation of the distribution should be further refined if appropriate.
- Secondary cues may reduce pre-movement times. Secondary cues will vary depending on the *design fire* and scenario being considered, ability of the occupant to recognise the cues and proximity to the source of the cue.

1.4.2 Category A Staff in Work Places

Category A is applicable to staff in workplaces (typically NCC Class 5, 6, 7, 8 and 9 buildings) where the staff can be considered to be awake and familiar. Suggested default pre-movement times are provided in Table 14. If the majority of the occupants are staff and any visitors are supervised the pre-movement times may be applicable to all occupants.

Table 14 Suggested Default Pre-movement Times for Category A Occupants

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time-s	Med %	Slow time-s	Slow. %	No resp %
XM1	XA1-2	XB1-2	30	10%	60	80%	90	10%	0%
XM2	XA1-2	XB1-2	60	10%	120	80%	180	10%	0%
XM1	XA1-2	XB3	60	10%	90	80%	120	10%	0%
XM2	XA1-2	XB3	90	10%	160	80%	210	10%	0%

With a minimal emergency management organisation (XM3) and training, substantially longer pre-movement times can be expected with large variances and in some cases, there may be no response from a significant % of occupants. If failure of the emergency management organisation is considered as part of a robustness check scenario it may be appropriate to assume 10% of occupants do not respond and adopt pre-movement times in the range of 15 to 30 minutes for the remainder.

In most cases these will be *accessible* buildings and there is a need to address evacuation of people with disabilities. Since the occupants are awake it will be assumed that adequate measures are in place to alert any occupants with disabilities and if necessary, provide assistance and therefore no adjustments are required to the above pre-movement times but evacuation strategies and travel speeds will require adjustment.

1.4.3 Category B Customer / Visitors to Shops, Restaurants and Large Entertainment Venues

Category B1 is applicable to customers / visitors to shops, restaurants and bars (typically NCC Class 6 buildings) and category B2 is applicable to cinemas and theatres (Class 9b *assembly buildings*, excluding schools). The occupants are expected to be awake and aware of the surroundings but may be unfamiliar with the building and the occupant density will be high. Suggested default pre-movement times are provided in Table 15.

Table 15 Suggested Default Pre-movement Times for Category B Occupants

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time-s	Med %	Slow time-s	Slow. %	No resp %
XM1	XA1-2	XB1	30	10%	90	80%	150	10%	0%
XM2	XA1-2	XB1	60	10%	150	80%	240	10%	0%
XM1	XA1-2	XB2	60	10%	120	80%	180	10%	0%
XM2	XA1-2	XB2	90	10%	180	80%	270	10%	0%
XM1	XA1-2	XB3	90	10%	150	80%	210	10%	0%
XM2	XA1-2	XB3	120	10%	210	80%	300	10%	0%

With a minimal emergency management organisation (XM3) and training, substantially longer pre-movement times can be expected with large variances and in some cases, there may be no response from a significant % of occupants. If failure of the emergency management organisation is considered as part of a robustness check scenario it may be appropriate to assume 10% of occupants do not respond and adopt pre-movement times in the range of 15 to 30 minutes for the remainder.

1.4.4 Category C1 Apartments

Category C1 is applicable to residents of apartment buildings (typically NCC Class 2 buildings). Generally, a fire occurring at night whilst occupants are asleep represents a worst-case scenario and the suggested default pre-movement times in Table 16 relate to occupants that are asleep, familiar with the building and are outside the SOU of fire origin.

Two sets of values have been provided based on the position of an apartment relative to the fire. FF refers to apartments on the fire floor and OF to other floors.

An A1 building-wide alarm system for an apartment building designed to the NCC DTS provisions may only be activated by a detector in a public space (corridor).

In many apartment buildings the emergency management organisation and training may be limited and there may be no response from a significant % of occupants especially as the distance varies from the floor of fire origin.

Table 16 Suggested Default Pre-movement Times for Category B1 Occupants that are Outside the SOU of Fire Origin

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time -s	Med %	Slow time -s	Slow. %	No resp %	Pos
XM2	XA1	XB1	150	9%	300	80 %	600	10%	1%	FF
XM3	XA3	XB1	300	8%	600	80 %	1200	10%	2%	FF
XM2	XA1	XB1	600	6%	1800	80 %	2400	10%	4%	OF
XM3	XA3	XB1	1200	2%	2400	80 %	3600	10%	8%	OF

The distribution of occupants of an apartment building can be assumed to be broadly representative of the general population of Australia and therefore the DOPs will need to include people with disabilities who may be less likely to respond to fire cues and the pre-movement times may be extended. Table 17 provides some suggested indicative values but these may vary considerably depending on the presence of a carer and severity of a disability and accessibility features of the building / apartment.

Table 17 Suggested Indicative Impact of Disabilities on Probability of Response and Pre-movement Times in Apartment Buildings

Activity	Pre-movement time increase- s	Probability of no response	Notes
Mobility	120-300	Similar to general population	Need to access wheelchair from bed.
Vision	120	Slight increase	Slower preparation time and no reinforcement from visual cues.
Hearing1	60-120	Significant increase	Slower response to visual alarm and potentially visual alarms less effective.
Cognitive / memory	120s	Large increase unless carer present	Less likely to recognise cues and slower to respond.

Note: It is assumed that visual alarms are provided. Refer Bruck et al[17] for data on waking effectiveness of alarms.

1.4.5 Category C2 Hotels / Motels

Category C2 is applicable to the guest rooms of hotel and motel buildings (typically NCC Class 3 buildings). Generally, a fire occurring at night whilst occupants are asleep represents a worst-case scenario and the suggested default pre-movement times in Table 18 relate to occupants that are asleep, unfamiliar with the building, and are outside the SOU of fire origin.

An A1 building-wide alarm system for an apartment building designed to the NCC DTS provisions may only be activated by a detector in a public space (corridor).

In mid and high-rise hotel buildings the emergency management organisation and training would be much more comprehensive than a typical apartment building, reducing the risk of no response from rooms remote from the fire.

Table 18 Suggested Default Pre-movement Times for Category B1 Occupants that are Outside the SOU of Fire Origin

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time-s	Med %	Slow time-s	Slow. %	No resp %
XM1	XA1-2	XB2-3	300	9%	600	80%	1800	10%	1%
XM2	XA1-2	XB2-3	600	9%	900	80%	2400	10%	1%
XM3	XA1-3	XB2-3	900	8%	1200	80%	3000	10%	2%

Hotels and motels are required to provide *accessible* rooms and the number of rooms provided can normally be used to estimate the highest proportion of guests with disabilities. Table 17 provides some suggested indicative values for apartments which may also be applied to hotels and motels but it should be noted that these may vary considerably depending on the presence of a carer and severity of a disability.

1.4.6 Category D Residential Care Buildings and Health-care Buildings

Category D is applicable to *residential care buildings* and *health-care buildings* (typically NCC Class 9a, 9c and some Class 3 buildings). It includes accommodation for the aged.

It is difficult to provide even indicative values for pre-movement times in *residential care buildings* and *health-care buildings* because residents and patients in many cases will require assistance from staff to prepare for evacuation and the subsequent evacuation process. The pre-movement times will therefore depend upon a large number of factors specific a building or facility including:

- staff ratios
- emergency management procedures (and associated emergency warning and intercommunication systems (EWIS)) in place which may allow for additional staff from other parts of the facility to be diverted to assist with the evacuation
- numbers of staff available to assist with the evacuation from other parts of a facility (this will vary with the size of the facility) and response time for these staff
- state of staff at time of fire (sleepover or awake)
- staff training
- evacuation strategy
- Travel time to move assisted occupants to a safer place before commencement of preparation of the next occupant
- patient / resident needs – preparation times will vary substantially depending on the status of the patient / resident. In some instances, evacuation may be impractical or expose patient to greater risk.

It is therefore critical that the evacuation management strategy is clearly defined in the PBDB and specifies matters such as patient (or resident) to staff ratios based on staff available to assist with evacuation, how these will be maintained at all times and the expected emergency management procedures to be followed for various scenarios including failure of the detection and EWIS. The PBDB stakeholders should include as far as practicable representatives with operational experience in similar facilities to ensure the evacuation management strategy will be appropriate and practical to implement.

Specific evacuation analyses should then be undertaken that incorporates activities such as:

- initial pre-movement times for staff close to fire and additional support staff from other areas to report to the ward or area being evacuated
- communication with patients / residents
- decision to evacuate and order of evacuation
- preparation of a resident or patient for evacuation
- evacuation of the resident or patient to a safe or safer area (depending on the strategy)
- return to commence preparation of the next occupant to repeat the process.

The analyses should consider staff fatigue and the presence of smoke. Sufficient numbers of staff required to safely evacuate an occupant to a safer place should be allocated. Further guidance is provided in Bennetts et al [18].

1.4.7 Category E Transportation Terminals

Category E is applicable to public areas in major transport terminals such as air, bus or rail terminals (typically, some NCC Class 9b buildings). Occupants are therefore assumed to be awake and aware of the environment but may not be familiar with the building which could have a complex layout.

Modern facilities are expected to have smoke detection systems with a voice alarm / PA and an emergency management organisation in place and the suggested default values in Table 19 assume this to be the case. Without these systems in place extended pre-movement times in excess of 15 minutes may occur.

Table 19 Suggested Default Pre-movement Times for Category E Transportation

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time-s	Med %	Slow time-s	Slow. %	No resp %
XM1	XA1-2	XB3	90	10%	165	80%	240	10%	0%

EMO	Det / Alarm	Build Complex	Prompt time-s	Prompt %	Med time-s	Med %	Slow time-s	Slow. %	No resp %
XM2	XA1-2	XB3	120	10%	210	80%	300	10%	0%

1.5 Travel Time

1.5.1 Derivation of Travel Time

To calculate the time for an occupant to travel between two positions it is often necessary to break the path of travel into a series of segments and connecting nodes to represent potential delays or transitions.

For each segment the travel speed of an occupant or occupant flow may be limited by:

- the occupant's capabilities
- congestion
- other members in a group the occupant is affiliated with
- restrictions in the dimensions of the path of travel
- poor visibility
- fatigue, etc.

Therefore, the time to travel a particular segment will depend to some extent on the time at which the occupant reaches that segment.

Delays can occur at nodes due to:

- queuing to enter a fire *exit* or path of travel
- waiting until instructed to leave during a phased evacuation
- waiting in a safer area for assisted evacuation
- recovering from fatigue
- waiting for assistance because the path of travel is blocked, etc.

These calculations can be undertaken by hand but for large populations with numerous DOPs the process is normally automated using spread sheets or proprietary models. The use and selection of models is discussed in more detail in Section 1.6.

> ***Alert***
>
> Paths of travel to *exits* and *exits* are required to comply with the relevant *Performance Requirements* of the NCC and for the *reference building* these must comply with the DTS provisions including requirements for accessibility. When determining compliance with the NCC any variations from these requirements for the proposed *Performance Solution* must be considered as part of the analysis.

For consideration of variations to accessibility provisions and planning for evacuation of people with disabilities reference should be made to the following publications:

- ABCB Handbook - Access Verification Methods[19]
- Evacuation Planning for Occupants with Disability [20]
- Emergency evacuation planning guide for people with disabilities [21].

To facilitate prompt evacuation of buildings, use may be made of lifts. Detailed information on the use of lifts for evacuation is outside the scope of this Data Sheet but the following documents provide useful information:

- ABCB Handbook, Lifts used During Evacuation [22]
- Vertical evacuation of vulnerable persons in buildings[23].

Tenability conditions should be checked in each enclosure on the path of travel and within *exits* to identify if any occupants have been exposed to untenable conditions during the evacuation.

1.5.2 Travel Speed

Reference should be made to the following for further details relating to application and the origins of the hydraulic method for calculating travel speeds and flow rates:

- SFPE Handbook of Fire Protection Engineering Chapter 59 Employing the hydraulic model in assessing emergency movement [24].

- ISO/TR 16738:2009 Appendix G[2].

If the population density is less than 0.54 persons/m^2 of the *exit* route, occupants will tend to move at their own speed independent of other occupants.

Although research has shown that walking speed varies with age and gender, a typical unimpeded walking speed of 1.2 m/s is considered a reasonable upper limit for adults. As the occupant density increases above 0.54 persons/m^2 occupants slow down and cease to move when the density exceeds 3.8 persons/m^2.

Travel speed, as a function of density and travel inclination, can be calculated by using Equation D1.2 below for the general population but some further reductions will be required to account for the aged and people with restricted mobility.

$$s = k - akD \qquad \text{Equation D1.2:}$$

where;

s= horizontal travel speed (m/s)

D= occupant density of the space (persons/m^2)

k= 1.4 for horizontal travel, and

a= 0.266.

The value of constant k varies depending on the travel inclination, and stair riser and tread size shown in Table 20.

For horizontal travel and travel along a ramp, the travel time should be calculated based on the travel speed for k=1.4 using equation 6-1. Therefore, the maximum speed using Equation D1.2 for an occupant density of 0.54 persons/m^2 will be approximately 1.2 m/s. For vertical travel via stairs, the travel time should be calculated based on the travel speed for the values of k listed in Table 20.

Table 20 Maximum Flow Rates for Vertical Travel Speeds Down Stairs (assumed density D = 0.54 persons/m^2)

Stair riser (mm)	Stair tread (mm)	k	Speed m/s*
191	254	1.00	0.85
178	279	1.08	0.95
165	305	1.16	1.00
165	330	1.23	1.05

The travel time (ttrav) for a segment is calculated by using Equation D1.3.

$$t_{trav} = L_{trav}/S$$ Equation D1.3

where:

t_{trav} =travel time (s), and

L_{trav} = travel distance (m).

The maximum horizontal travel distance (Ltrav) must be determined by the greater of either:

(a) the measured length around furniture and other obstructions if this is known, or
(b) adding together the length and width measurements of the room.

1.5.3 Flow

The specific flow, Fs is the flow of evacuating persons past a point per unit of time per unit effective width and is given by Equation D1.4.

$$F_s = SD$$ Equation D1.4

where:

Fs = specific flow (persons/sec), and

D = occupant density of the space (persons/m^2), and

S= Speed of Movement (m/s).

Combining Equation D1.2 and Equation D1.5 yields

$$F_c = (1 - aD)kDW_e$$ Equation D1.5

where:

Fc = calculated flow (persons/sec)

D = occupant density of the space (persons/m^2)

We =effective width of component being traversed in metres.

The W_e is equal to the measured width minus the boundary layer, where the thickness of the boundary layer is obtained from Table 21.

Table 21 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

Equation is most commonly used for doorway flows to estimate the queuing times but is not suitable for people with mobility impairment.

1.5.4 Reduced Speed in Low Visibility Conditions

The outcomes of a recent review of studies quantifying walking speed and visibility were reported by Fridolf et al [25] which found that there was a lack of reliable and valid correlations for predicting peoples' walking speed in smoke. This led to the initiation of a research project with the goal of summarising the current knowledge base and to describe and recommend how it can be used in practical application.

A threshold visibility value below which people in general can be expected to start reducing their walking speed was found to be approximately 3 m (based on light reflecting sources with non-irritant smoke).

Visibility can be calculated from the extinction coefficient using Equation D1.6 Jin[26].

$V = k_e / C_s$ Equation D1.6:

where:

V= visibility (m)

C_s = extinction coefficient (m-1)

k_e = empirically determined constant (in the range of 5-10 for light emitting signs and 2 to 4 for reflective signs).

The lower coefficients in each range have been adopted to calculate the extinction coefficients (Cs) corresponding to visibility values for light emitting and reflective signs in Table 22.

Table 22 Visibility and Corresponding Extinction Coefficients for Light Emitting Signs and Reflective Signs

Visibility - m	Cs -m-1 for light emitting signs (k=5)	Cs -m-1 for reflective signs (k=2)
3.0	1.67	0.67
4.0	1.25	0.50
5.0	1	0.4
6.7	0.75	0.30
7.5	0.67	0.27
10.0	0.5	0.2
12.5	0.4	0.16
16.7	0.3	0.12
25.0	0.2	0.08

From a review of Table 22 it can be observed that the visibility of non-irritant smoke with an extinction coefficient of 0.67 m-1 is 3.0 m for reflective signs and 7.5 m for light emitting signs. Since the FSVM 5 m tenability limit for visibility applies to small rooms, if an illuminated *exit* sign is provided the walking speed for non-irritant smoke would be unlikely to be exceeded prior to the onset of untenable conditions.

There has been very limited work on the impact or irritant smoke but the work that has been carried out in this area by Jin has been summarised (Jin [26]) and shows slower walking speeds in irritant smoke for extinction coefficient values above approximately 0.2 m-1. Table 23 which has been extracted from a chart in Jin [26] shows the rapid reduction in walking speed as the extinction coefficient increases from this point.

Table 23 Extinction Coefficient and Speed Derived from Jin [26]

Extinction coefficient (Cs) m-1	Speed m/s
0.2	1.1
0.3	1
0.4	0.84
0.5	0.3

Since factors other than visibility such as eye irritation and the psychological impact may become more relevant with irritant smoke the walking speed is assumed to be more closely linked to the extinction coefficient (and hence smoke concentration) rather than visibility which varies between light emitting and reflective surfaces.

The 10 m and 5 m visibility tenability limits for light emitting signs corresponds to extinction coefficient of 0.5 m-1 and 1 m-1 respectively and therefore the walking speeds would be expected to be 0.3 m/s or less at the onset of the tenability criterion for irritant smoke.

For most applications it is not possible to avoid the risk of production of irritant smoke and therefore, subject to agreement by the PBDB stakeholders the following approach may be considered appropriate.

Alert

When using the FSVM the modification factors specified in Table 24 should be applied to the average travel speeds calculated in accordance with Section 1.5.2. When the visibility drops below 10.0 m with light emitting signs it should be assumed that the occupants will either try to find an alternative escape path or safer place and wait for assistance.

Table 24 Suggested Modification Factors for Speed When Occupants Are Exposed to Irritant Smoke.

Visibility with light emitting signs -m	Extinction coefficient Cs -m-1	Walking speed modification factor
10.0	0.5	0.3
12.5	0.4	0.7
16.7	0.3	0.9
25.0	0.2	1.0

1.5.5 Evacuation Speeds for People with Reduced Mobility

ISO/TR 16738:2009 Appendix G[2] provides tabulated speeds collated from referenced literature for the movement of people with reduced mobility using various aids.

For assisted evacuation in a hospital environment, Hunt [27] provides a detailed analysis and numerical simulation of the performance of hospital staff using movement assist devices to evacuate people with reduced mobility. A brief summary is provided in Bennetts et al[18].

1.6 Evacuation Models

For complex buildings with large populations in particular it is impractical to undertake hand calculations and it is necessary to rely on computer models.

These can simply be automated hand calculations or allow for the integration of some aspects of human behaviour.

It is critical that there is a clear understanding of the assumptions and methods integrated into a model and that the results are checked against available drills, exercises and published studies of fire events e.g. Gwynne and Boyce [16].

It is not appropriate to include a review of proprietary evacuation models in this Data Sheet but a review of computer evacuation models and a description of an appropriate selection and testing process are provided by Kuligowski [28] and in the SFPE Guide to Human Behaviour in Fire Second Edition[4].

A brief summary of the key steps to be undertaken by users to select appropriate models for a particular application are summarised below:

- Define project specific requirements – these will vary depending upon the factors such as the complexity of the building, building population and extent and relevance of the variations under consideration to evacuation of the occupants.
- Select candidate models depending upon their suitability for the specific application. The capabilities and limitations of the model should be considered along with pre-existing validation relevant to the analysis being undertaken. Where aspects of human behaviour and the influence of the emergency management organisation are important to the outcomes the model should be able to account for these either directly or indirectly by adjustment of inputs and incorporation of delays / decision making.
- Determine that the model outputs provide all the information to compare results for the *reference building* and proposed *Performance Solution*.
- Once a model is selected it is necessary to verify the operation of the model by, for example, evaluating simple test cases to confirm travel speeds, delays and congested flow calculations are in accordance with the model documentation.
- The model and results for the subject building should then be validated and calibrated against available technical literature, drills and exercises on similar buildings where available. A useful compilation of data has been provided by Gwynne and Boyce[16].
- Sensitivity analysis should be undertaken to:
    - determine that the model results vary in a manner expected. Where unexpected results are obtained it does not necessarily indicate an error but investigations should be undertaken to understand the reasons for the unexpected results and determine if they are valid and reasonable.
    - that the ranking of the *reference building* and proposed *Performance Solution* are not changed by viable variations in inputs.

1.7 References

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APPENDICES

Appendix A Abbreviations

The following table, Table A.1 contains acronyms and symbols used in this document.

Table A.1 Acronyms

Acronym/Symbol	Meaning
ABCB	Australian Building Codes Board
ASET	Available Safe Egress Time
DOP	Design Occupant Profile
DTS	Deemed-to-Satisfy
EMO	Emergency Management Organisation
FIP	Fire Indicator Panel
FSVM	Fire Safety Verification Method
NCC	National Construction Code
PBDB	Performance-Based Design Brief
PBDR	Performance Based Design Report
RSET	Required Safe Egress Time
IFEG	International Fire Engineering Guidelines
FED	Fractional Effective Dose

Appendix B Defined Terms

B.1 NCC Defined Terms

NCC definitions for the terms used in this document can be found in:

- Schedule 3 of NCC 2019 Volumes One, Two and Three.

Building classifications can be found in:

- Part A6 Building Classifications of NCC 2019 Volumes One, Two and Three.

1.8 B.2 NCC Terms

These definitions have been reproduced from the NCC but where appropriate supplementary content has been provided in boxed brackets to clarify the definitions further in relation to the FSVM and this document.

In this document, NCC terms are italicised to indicate they have a specific meaning under the NCC.

Appropriate authority as defined in the NCC means the relevant authority with the statutory responsibility to determine the particular matter.

[To provide clarity of terminology for the specific application of the *appropriate authority* determining compliance with the *Performance Requirements* the definition of *appropriate authority* is expanded to mean the relevant authority with the statutory responsibility to determine the matter satisfies the relevant *Performance Requirements*.]

Note 1: This is typically the building surveyor charged with the statutory responsibility to determine building compliance and issue the building permit / approval and occupancy certificate / approval.

Note 2: Some jurisdictions refer to a building surveyor performing these functions as a building certifier.

Available safe egress time (ASET) means the time between ignition of a fire and the onset of untenable conditions in a specific part of a building. This is the calculated time interval between the time of ignition of a fire and the time at which conditions become such that the occupant is unable to take effective action to escape to a place of safety.

Building Solution means a solution which complies with the NCC *Performance Requirements* and is a—

(a) *Performance Solution*; or

(b) *Deemed-to-Satisfy Solution*; or

(c) combination of (a) and (b).

Design fire means the quantitative description of a representation of a fire within the *design scenario*.

Design scenario (reference *design scenario*) means the specific scenario of which the sequence of events can be quantified, and a *fire safety engineering* analysis conducted against.

Fire-resistance level (FRL) means – the nominal grading period, in minutes, that is determined by subjecting a specimen to the standard time-temperature curve regime set out in AS 1530.4, to specify:

(a) structural adequacy
(b) integrity
(c) insulation

and expressed in that order.

[Other criteria are sometimes nominated including:

- the resistance to incipient spread of fire
- the ability of a service to maintain its design operating capacity (function).]

Fire safety engineering means application of engineering principles, rules and expert judgement based on a scientific appreciation of the fire phenomenon, often using specific *design scenarios*, of the effects of fire and of the reaction and behaviour of people in order to:

- save life, protect property and preserve the environment and heritage from destructive fire
- quantify the hazards and risk of fire and its effects
- mitigate fire damage by proper design, construction, arrangement and use of buildings, materials, structures, industrial processes and transportation systems
- evaluate analytically the optimum protective and preventive measures, including design, installation and maintenance of active and passive fire and life safety systems, necessary to limit, within prescribed levels, the consequences of fire.

Heat release means the thermal energy produced by combustion (kJ).

Heat release rate (HRR) means the rate of thermal energy production generated by combustion (kW (preferred) or MW).

Performance-based design brief (PBDB) means a process and the associated report that defines the scope of work for the *fire safety engineering* analysis and the technical basis for analysis as agreed by stakeholders. [Note: The term Fire Engineering Brief (FEB) was used in the IFEG 2005 and other related guidance material for the equivalent of a PBDB. The PBDB is a general term relating to all disciplines.]

Performance Requirement means a requirement which states the level of performance which a *Performance Solution* or *Deemed-to-Satisfy Solution* must meet.

Performance Solution means a method of complying with the *Performance Requirements* other than by a *Deemed-to-Satisfy Solution*.

[The term *Performance Solution* refers to the entire building including any management procedures that are required to ensure the fire safety strategy satisfies all the relevant NCC *Performance Requirements* throughout the life of the building and must address all variations from the DTS compliant *reference building*]

Reference building, for the purposes of Volume One, means, depending on the application-

a hypothetical building that is used to calculate the maximum allowable annual energy load, or maximum allowable annual greenhouse gas emissions and determine the thermal comfort level annual energy consumption for the proposed building.

[or in the context of the FSVM, a hypothetical building that complies with the fire safety DTS building and is used as a benchmark for the assessment of a *Performance Solution* using the FSVM].

Required safe egress time (RSET) means the time required for safe evacuation of occupants to a place of safety prior to the onset of untenable conditions.

Verification Method means a test, inspection, calculation or other method that determines whether a *Performance Solution* complies with the relevant *Performance Requirements*.

Visibility means the maximum distance at which an object of defined size, brightness and contrast can be seen and recognised.

B.2 B.3 Other Terms

Design Occupant Profile (DOP) means a characterisation or profile of an occupant or group of occupants that will recognise and respond to cues in a similar manner and time and evacuate at a similar speed with a similar vulnerability to fire effluents and heat. The building population can be assigned to a series of DOPs in proportion to the numbers likely to be present during a *design scenario*.

Detection time means the time interval between ignition of a fire and its detection by an *automatic* or manual system.

Emergency management organisation (EMO) comprises the management structure, procedures and resources for dealing with all aspects of a fire emergency to reduce the potential harm.

Evacuation management strategy means a strategy that documents the minimum requirements and performance that is expected during a fire emergency to facilitate the evacuation of all occupants of a building efficiently and in an orderly and as far as practicable equitable manner. The *emergency management strategy* should include details of:

- the emergency management organisation that is or will be in place
- detection and EWIS systems and other means of notification and intercommunication
- construction and configuration of paths of travel to *exits* and fire *exits*
- alternative means of evacuation e.g. lifts
- evacuation procedures including how the evacuation will be managed
- provisions to facilitate evacuation of people with disabilities
- requirements for training and drills
- expected evacuation performance.

Fire decay means the stage of fire development after a fire has reached its maximum intensity and during which the *heat release rate* and the temperature of the fire are generally decreasing.

Fire growth means the stage of fire development during which the *heat release rate* and the temperature of the fire are generally increasing.

Fire safety engineer (or fire engineer) means a *professional engineer* with appropriate experience and competence in the field of *fire safety engineering*.

Fire safety level is a general term which can be considered the reciprocal of the fire risk such that if the risk to occupants from fire is reduced the fire safety level is increased.

Fire safety strategy means a combination of physical fire safety measures and human measures / factors including maintenance and management in use requirements which have been specified to achieve the nominated fire safety objectives.

Fully developed fire means the state of total involvement of the majority of *combustible* materials in a fire.

Pre-movement time means the time from notification until evacuation begins.

Recognition time means the period after an alarm or cue is evident but before an occupant of a building begins to respond.

Response time means the period after occupants recognise the alarms or cues and begin to respond to them but before they begin the travel phase of evacuation or travel to a safer place within the building depending on the fire safety strategy and *design scenario* under consideration.

Travel distance means the distance that is necessary for a person to travel from any point within a built environment to another point, taking into account the layout of walls, partitions and fittings.