Is Prescription the Future of Performance-Based Design?

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ABSTRACT

The popularity of performance-based design (PBD) has continued to increase over the last two decades and many consider PBD provides cost effective and innovative solutions to fire safety challenges. Fundamental to PBD for life safety, is the principle that the occupants have enough time to exit the building before being overcome by the fire. In fire engineering terms the available safe egress time (ASET) must exceed the required safe egress time (RSET) with an appropriate margin of safety. Currently the necessary input and acceptance criteria are left up to the designer to decide with the approval from the authority having jurisdiction (AHJ). Unfortunately the conventional guidance on design scenarios, design fires and acceptance criteria are typically more qualitative than quantitative in nature which often leads to widely varying interpretation and significant differences in the safety levels for buildings that are substantially similar. This paper reviews the current guidance on design scenarios, design fires and acceptance criteria necessary for an ASET versus RSET analysis as well as highlighting areas where additional research is needed. The paper ends with a brief description of the new verification method that the Department of Building and Housing is proposing for PBD in New Zealand. The Verification Method (VM2) outlines the design fire scenarios, design fires, pre-movement times and acceptance criteria that are currently being reviewed after the public comment period.

KEYWORDS: performance-based design, fire scenarios, design fires, acceptance criteria, pre-movement times.

INTRODUCTION

For as long as there has been civilization we have been plagued by the risk of fire. As our civilizations have evolved so has our ability to protect the structures which make up our urban developments from the ravages of unwanted fires. The protection of our civilization from fires has typically been through the evolution of our building regulations. Over time these regulations have changed and evolved with societal expectations. In general this evolution of our regulations has been reactionary to large fire events which are deemed to be unacceptable to society. Over the last century and a half fire codes have evolved from simple urban spread reduction to protecting individual buildings and ultimately to protecting life.

For nearly two decades performance-based design (PBD) has evolved and is now being touted as the future of building design for fire safety providing for cost effective and innovative solutions to fire safety challenges. Although PBD continues to grow in popularity and sophistication, fire engineering has yet to reach the same level of understanding compared with the more traditional disciplines where PBD is common. Fire engineering is still a rapidly developing discipline with new methodologies and understanding evolving continuously. For example, it has only been in the last five years that CFD modeling has become common practice for complex fire engineering analysis, where a decade ago only universities and research institutions had the necessary computing power. Since 1996 the Society of Fire Protection Engineers (SFPE) has held a biennial international conference on performance-based codes and design methods to highlight the latest developments in performance-based fire safety research and design.

At the very heart of PBD for life safety is the fundamental principle that the occupants have enough time to exit the building before being overcome by the fire. In fire engineering terms, the available safe egress time (ASET) must exceed the required safe egress time (RSET) with an appropriate margin of safety. The ASET is calculated using a computer model to estimate the time to untenable conditions based on the agreed performance criteria. The RSET is an estimate of the time required for the occupants to be alerted to the fire and evacuate the building. There are a number of books [1], guides [2,3] and codes [4] on PBD and many countries allow for performance-based solutions to design issues. One of the most comprehensive codes that include a performance-based option is the National Fire Protection Association Life Safety Code [4] (NFPA101). NFPA101 lays out eight scenarios that must be used to evaluate a proposed building design. However the sce-

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narios and supporting performance clauses of the code are very qualitative in nature and do not provide quantitative advice about the design fire, acceptance criteria, or methodology but simply outline all of the factors that should be considered by a designer without actually quantifying any of the necessary input parameters or acceptance criteria. This leaves the designer having to develop their own criteria and design input with the approval of the authority having jurisdiction (AHJ). This lack of quantified guidance forces the designer to turn to the literature and pull together the required input and performance criteria from a number of sources to carry out their analysis.

Under the current approach, without quantified guidance, there is significant variability in the design fire scenarios, design fires and acceptance criteria. For example, in one building the designer evaluates the fractional effective dose (FED) at 2 m above the floor yet in another design the designer calculates the FED at 1.8 m. In many cases the local AHJ is reluctant to challenge the fire engineer's recommendations for the design fire and performance criteria because the AHJ often has a different qualification than the fire engineer. This can lead to inconsistent levels of fire safety in buildings of similar occupancy.

This paper reviews the available guidance for the ASET versus RSET analysis used in PBD, specifically, design fire scenarios, design fires, acceptance criteria, and pre-movement times. The paper outlines the areas where additional research is needed to assist the designer in making more informed decisions for PBD. The paper ends with a brief description of the new verification method (VM2) that the Department of Building and Housing, the New Zealand building regulator, is proposing for PBD which specifies the design fire scenarios, design fires, pre-movement times and acceptance criteria that may be specified for PBD in the future.

FIRE SCENARIOS

Current Methodology

Fundamental to any fire safety evaluation process are the design fire scenarios. In the context of this paper, a fire scenario is a qualitative description that characterizes the key events of a potential fire. A design fire scenario is a description of a specific fire scenario that is used in a fire safety engineering analysis. Typically the design fire scenarios are used in deterministic analysis such as an ASET versus RSET analysis or may simply dictate particular performance requirements such as the allowable surface spread of flame in exitways. There are an infinite number of potential fire scenarios and it is typically up to the fire engineer to reduce the fire scenarios to a manageable number and use deterministic methods to evaluate the consequences of the scenarios in the proposed building against the performance criteria.

There are a number of references which discuss the various aspects of choosing fire scenarios [1,2,5]. The International Standards Organization technical committee TC92 developed ISO/TS16733: *Fire safety engineering – Selection of design fire scenarios and design fires* [6], outlining a 10-step comprehensive procedure which includes an event tree to help reduce the number of design scenarios to a manageable level. The 10 steps are:

1. Location of fire – select fire locations that produce the most challenging fire scenarios.
2. Type of fire – identify the most likely types for fire scenarios and most likely high consequence fire scenarios based on fire incident statistics.
3. Potential fire hazards – identify other critical high consequence scenarios for consideration.
4. Systems impacting on fire - identify the building and fire safety systems that are likely to have a significant impact on the fire or development of untenable conditions.
5. Occupant response – identify occupant characteristics and response features that are likely to have a significant impact on the course of the fire scenarios.
6. Event tree – develop event tree that represents the possible factors that have been identified as significant.
7. Consider probability – estimate the probability of occurrence of each state using the available reliability data and engineering judgment when data is not available.
8. Consideration of consequence – estimate the consequences of each scenario using engineering judgment.
9. Risk ranking – rank the scenarios in order of relative risk.

10. Final selection and documentation – select the highest-ranked fire scenario for quantitative analysis.

The National Fire Protection Association (NFPA) has taken a different approach to developing fire scenarios for use as a performance-based option in their Life Safety Code [4] and Building Construction and Safety Code [7]. In each of these codes the NFPA has identified eight scenarios that must be analyzed and compared to the performance criteria. The eight required scenarios include:

1. Occupancy specific fire representative of a typical fire for the occupancy.
2. An ultra-fast developing fire in the primary means of egress, with interior doors open at the start of the fire.
3. A fire that starts in a normally unoccupied room, potentially endangering a large number of occupants in a large room or other areas.
4. A fire that originates in a concealed wall or ceiling space adjacent to a large occupied room.
5. A slowly developing fire, shielded fire protection systems, in close proximity to a high occupancy area.
6. Most severe fire resulting from the largest possible fuel load characteristics of the normal operation of the building.
7. External exposure fire
8. Fire originating in ordinary combustibles in a room or area with each passive and active fire protection system independently rendered ineffective.

Additional scenarios may also be specified by the design team or authority having jurisdiction. According to the NFPA, additional scenarios should be considered and suggest that as a minimum the following three types of scenarios be considered:

1. High-frequency, low-consequence scenarios
2. Low-frequency, high-consequence scenarios
3. Special problems scenarios

The additional scenarios are intended to take into account the unique characteristics of the building.

Research Needs for Design Fire Scenarios

Although the NFPA and ISO/TC92 documents give very detailed discussion for developing the fire scenarios, they do not specify the design fires that are required to carry out the fire safety evaluations for a building. Thus it is left to the fire engineer to come up with the design fire scenarios with all of the stake holders during the fire engineering brief (FEB) process outlined in the International Fire Engineering Guidelines [8] (IFEG). However, there is a notable lack of consensus about what scenarios should be included in a PBD and most of the discussion in the literature is very qualitative. Recently the SFPE carried out a study to identify the technical priorities for the future[9]. In this study the first priority was to develop a standard that provides prescribed design fire scenarios for use in PBD for a variety of occupancies and situations.

The scenarios outlined in NFPA101 go a long way to assisting in the creation of the appropriate design scenarios. Many of the scenarios appear to be based more on anecdotal evidence rather than being statistically justified. In the 10 steps outlined in ISO/TS16733 there are a number of areas where future research is needed. Most obvious is in the area of statistical information about fire incidents. Many government organizations such as the United States Fire Administration (USFA) and the Fire Statistics and Research Division (FSRD) in the UK collect fire incident data and carry out statistical analysis of this data. Unfortunately the data collected typically provide only limited information that is needed for fire design scenario development. Although the data can be useful in many cases, often many details of interest are simply not available. Regrettably, details such as: effectiveness of suppression systems, effectiveness of venting, barrier performance, occupant response, etc., are simply not available and the obtainment of the desired information is difficult, expensive and is not expected to be achievable in the foreseeable future. Ultimately the profession would benefit from significantly more detailed investigations of all fires, however, only incidences of suspicious origin receive detailed investigations.

DESIGN FIRE

Current Methodology

Each of the design fire scenarios is qualitative in nature and requires a quantitative design fire for use in a fire safety assessment. A design fire is intended to represent a credible worst case scenario that will challenge the fire protection features of the building. Although simple in concept, this definition can be hard to interpret when attempting to quantify the design fire especially in low ceiling spaces where occupants are expected to be sleeping. Typically the design fire is described in terms of the heat release rate from the fire. Indeed, the heat release rate history is considered the single most important variable in describing a fire hazard [10]. However, the design fire often includes an estimate of the size of the fire, the species production rates, and the effective heat of combustion. Unfortunately it is not possible to derive the design fire from first principles and can be quite difficult to quantify in practice. The detail required for a design fire is dependent on the issue being investigated and what questions the engineer is trying to answer. For example it is not of much use to have a design fire that includes the decay phase if the engineer is trying to predict the activation of a sprinkler head. Likewise, the growth phase makes little difference if the engineer is trying to model the fire resistance of a structural member after four hours of fire exposure. Thus the nature of the design fire depends on the issues the fire engineer is resolving. In this section the components of the design fire i.e., growth rate, species production rate, and effective heat of combustion are descried in some detail with the research needs described at the end of this section.

Fire Growth Rate

Figure 1 shows the idealized fire growth rate history highlighting the four phases of conventional fire development and the transition of flashover.

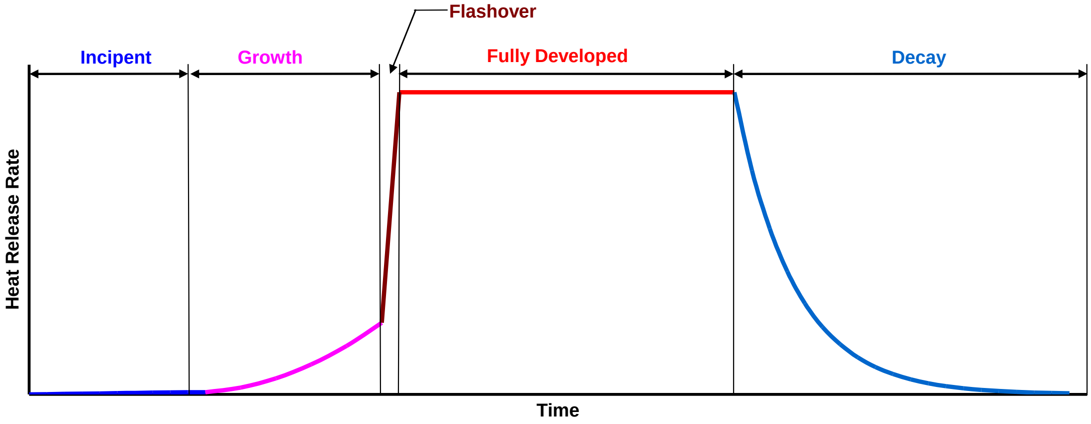


Fig. 1. Idealized heat release rate history highlighting the four phases of conventional fire development and flashover.

The **incipient phase** of a fire can last from a few seconds to days depending on the initial fuel involved, ambient conditions, ignition source, etc. In the case of a flammable liquid spill the incipient phase is effectively nonexistent. If it is a case of self-heating to ignition, the incipient phase can last for hours if not days. In some cases the fire may not grow beyond the incipient phase, consider a cigarette which smolders on a wool fabric may never ignite the flammable padding beneath the fabric. There are far too many variables to allow for reliable modeling of the incipient phase of a fire. Indeed, for the furniture calorimeter test a gas burner is used to simulate a wastepaper basket to eliminate the impact of the incipient phase on the early growth phase.

The **growth phase** is considered to begin when the radiation feedback from the flame governs the burning rate. Assuming the compartment is vented, the growth rate is primarily governed by the fuel properties and orientation. During the growth phase the fire spreads across the fuel surfaces, increasing the burning area and corresponding heat release rate. The heat release rate is assumed to be independent of the fire enclosure and governed more by the flame spread rate. Compartment enhancement due to the accumulation of hot gases is considered small until the fire nears flashover.

Modeling the actual growth rate is extremely difficult and remains an area of active research. It is dependent on many factors which are not only a function of the burning object but are also stochastic in nature such as size and location of the ignition source, orientation of the object, proximity to other objects, proximity to boundaries, proximity to openings, etc. Notwithstanding these limitations, the fire engineer must rely on judgment when choosing a growth rate. It is true that most fires occurring during the life of a building will be quite minor and are likely to go unreported; it is the reasonable worst case fire and not the most likely fire that must be used for design.

There are several approaches to estimating the growth rate for a particular design fire. The most popular is the *t*-squared fire growth rate. Originally developed in the 1970s for predicting fire detector activation, the *t*-squared fire gained popularity when it was included in the appendix of NFPA72 [11]. In NFPA72 there are three categories for fire growth slow, medium, and fast. These definitions are simply determined by the time required for the fire to reach 1055 kW (1000 BTU/s). A slow fire is defined as taking 600 s or more to reach 1055 kW. A medium fire takes more than 150 s and less than 300 s and a fast fire takes less than 150 s to reach 1055 kW. Over time the definition for a *t*-squared fire has evolved to include an ‘ultra fast’ fire as well. The common definition for the growth times are shown below:

$$\dot{q} = \alpha t^2 \qquad (1)$$

The *t*-squared fire growth can be thought of in terms of a burning object with a constant heat release rate per unit area in which the fire is spreading in a circular pattern at a constant flame speed. Obviously more representative fuel geometries may or may not produce a *t*-squared fire growth. However, the implicit assumption in many cases is that the t-squared approximation is close enough to make reasonable design decisions [12]. It should be noted that the t-squared growth rate has been adopted well beyond the original intent in some cases for fires as large as 30 MW. Such application has been questioned in the literature [13].

When deciding on the most appropriate growth rate there are a number of sources available that provide some guidance on the selection but there are few recommendations available for the most appropriate design fires for engineering. ISO/TS16733 is one such guidance document that provides detailed advice about choosing a design fire but does not recommend values. Unfortunately the available guidance requires a great deal of data that typically is not available. This leaves the decisions regarding the design fires up to the engineer and can make it challenging for the approving authority to evaluate a design.

Flashover occurs when the radiation from the upper layer is so intense that all of the combustible surfaces in the compartment ignite. Flashover can be thought of as a transition from a small fire to full room involvement. This transition typically occurs over a short time span measured in seconds. From an experimental point of view flashover is considered to occur when the upper layer temperature reaches 500–600 °C. The increase in radiation from the upper layer not only ignites all of the combustibles in the room but also enhances the heat release rate of all the burning objects. From a design point of view, flashover is typically modeled as a linear transition from a growing fire to a fully developed fire over a very short period of time.

In the post-flashover/fully developed phase of the fire all of the combustible objects in the compartment are burning and the heat release rate is either limited by the fuel surface area or the available air supply. Typically it is the available air supply that governs the post-flashover phase except in the cases of very large openings or low combustible surface areas. The mass of air that flows into an opening can be estimated using the well known A-root-H correlation first identified by Kawagoe when reducing post flashover fire data in 1958 [14]. The heat release rate within the compartment ($\dot{q}_{inside}$) can then be estimated using the assumption that most fuels release a constant amount of energy per unit mass of air consumed, that is 3.0 MJ/kg$_{air}$.

$$\dot{q}_{inside} = 1.5 A_0 \sqrt{H_0} \qquad (2)$$

It should be reiterated that this is the energy that is released inside the compartment. In many cases the burning objects actually release more fuel vapor than can be consumed within the compartment, i.e. the fire is ventilation limited which can fuel very long flames out of the opening [15].

The **decay phase** occurs when the fire has consumed much of the available fuel and the heat release rate starts to diminish. During the decay phase the fire will typically transition from ventilation-controlled to surface area-controlled. This is primarily of interest when determining the required fire resistance of structural elements. This phase of the design fire curve is the least studied and least understood. In most cases firefighter intervention prevents or at least interferes with the fires' decay.

In addition to the heat release rate the gas species and heat of combustion are also necessary for a complete description of the design fire. Typically a fire model requires the species to be input as a production rate, i.e. mass of species per mass of fuel consumed. For ASET calculations at least the carbon dioxide and carbon monoxide are necessary to calculate the FED. The effective heat of combustion is also necessary to convert the heat release rate into a mass loss rate in order to obtain the species production. In some cases, it may be necessary to define the species production rate as a pre-flashover and a post-flashover value to account for the impact that the ventilation can have on the species production. For this discussion the complete description of the design fire includes the heat release rate history, the hydrogen to carbon ratio of the fuel, the effective heat of combustion, and the species production rates for the carbon dioxide, carbon monoxide and other toxic species.

Research Needs in Design Fire

Although the area of design fire research can be extremely broad covering topics from advanced combustion chemistry to straightforward standardized testing of the heat release rate of burning objects, the discussion here focuses on the direct requirements for PBD. There are a number of studies in the literature that give experimental results for the heat release rate histories for burning objects. There are many published documents that provide useful overviews of the literature, particularly Refs. [10,16]. All too often engineers rely on only a small collection of data from a single source for their fire growth rates for PBD. However, more comprehensive studies such as the work by Young [16], which looked at a number of publicly available data sources for upholstered furniture fires, are needed to allow designers to make more informed decisions regarding the fire growth rate. In Young's study, 140 single seat upholstered furniture items were investigated to determine the range of fire growth rates. Data was taken from a number of sources including the EC-CBUF [17] data and similar studies in New Zealand [18,19,20]. All furniture items were ignited with the California TB-133 30 kW gas burner [21] and the fire growth rate was simply defined by the time taken to reach 1055kW. Figure 2 shows the fire growth rate constants (α) for all the 140 chairs along with the α values for the ultrafast, fast, and moderate fire growth definitions. Ultimately the growth rate constant chosen for a particular fire growth rate is up to the regulator based on the agreement of all stakeholders, but comprehensive reviews of the available literature as shown here are very valuable to the designers and AHJ when choosing the most appropriate growth rate for PBD.

Most of the fire research on design fires has focused on a single burning item yet in most real compartments; there are a number of items that contribute to the fore development. Typically the practitioner takes a deterministic approach and assumes the design fire based on the item with the highest growth rate among the items expected within the compartment. However, the problem is far more complicated and is more appropriately dealt with in stochastic methodology. Issues such as how close are the objects within the compartment, what are the ignition and growth characteristics, what are the species production rates, how large is the room, are only a few of the possible variables that impact the design fire. Recent work [22] has focused on the development of a probabilistic design fire generator using a zone model for the deterministic variables and Monte-Carlo simulations approach to address stochastic variables. Eventually such models may become common in PBD.

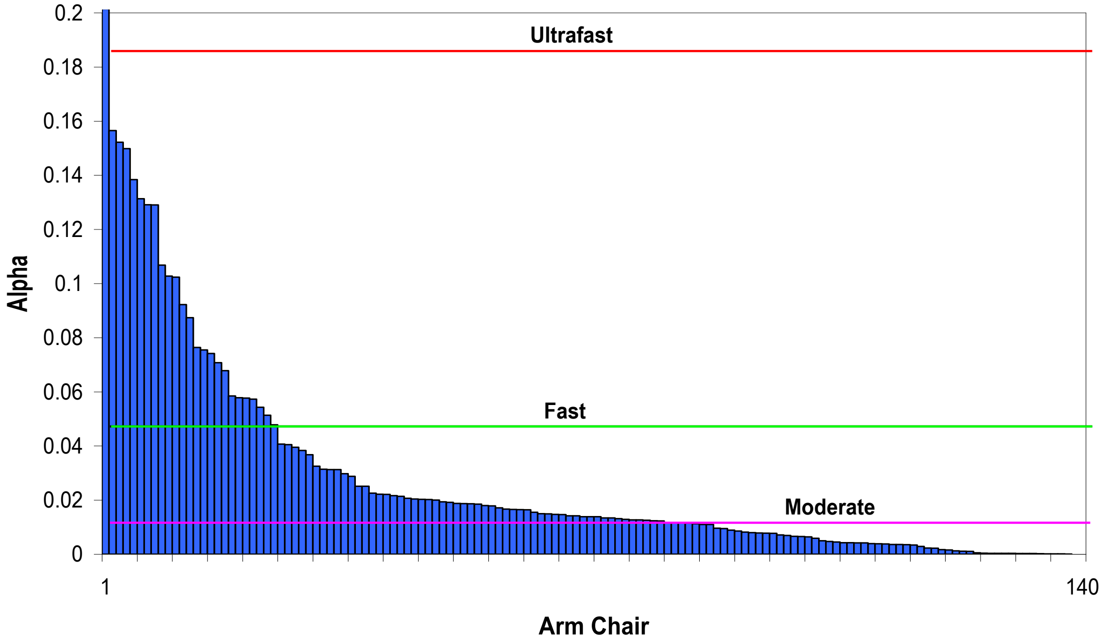


Fig. 2. *t*-squared fire growth constants for 140 single seat upholstered furniture items along with the medium, fast, and ultrafast values.

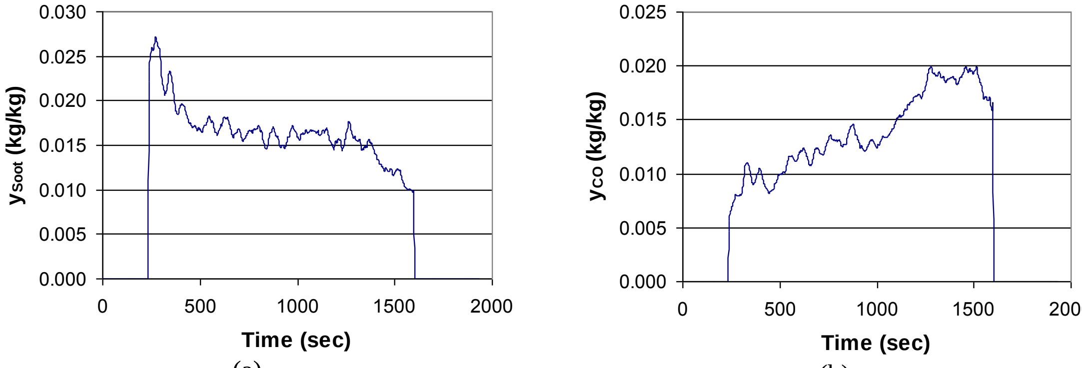
Unfortunately, much of the data in the literature fails to give a complete description of the other data that is needed for the ASET analysis. Although there are many sources of data for heat release rate, these often do not include the species, or only give the gas concentrations measured in the duct but not the species production rate that is required for fire modeling. Often the mass loss rate is not measured, which makes it impossible to determine the species production rate sufficiently accurate for engineering analysis. There are a number of sources available in the literature for the species production rate measured in the laboratory scale experiments such as the ASTM1354 cone calorimeter or ASTM E2058 fire propagation apparatus designed by Factory Mutual Research Corporation. There is an extensive collection of experimental data in Tewarson's chapter of The SFPE Handbook [23]. However there is significant variance in the values reported within the literature, even within The SFPE Handbook. Table 1 shows the soot yield, carbon monoxide yield, and effective heat of combustion taken from the literature with the source of the data given in the last column. The data given in Table 1 are nominally for the same fuels, i.e. flexible polyurethane and wood, which demonstrates the wide range of values that can be found in the literature. Although nominally for the same fuel, e.g. flexible polyurethane, there is more than an order of magnitude difference in the soot yield ranging from 0.01 to 0.23. For the carbon monoxide yield the range is not as broad and only varies by a factor of 4. The effective heat of combustion varies by ± 22 %. The wide range in the properties is due to a number of factors including, but not limited to, different combustion conditions in the test methods and changes to the chemical composition due to different additives in the foam. A narrower range in the yields and ΔH_c can be seen for the wood values given in Table 1, but is still much wider than hoped. These wide ranges in the data make it difficult for the engineer to select a value for their analysis.

The species yields mentioned above are average values over the experiments for pure materials. However, fires typically involve a virtual potpourri of materials that may be involved in the fire at different times. For example an item of upholstered furniture typically includes the fabric, foam, and timber frame. When an item of furniture is burned the species yield is time-dependent, which further complicates the selection made by the designers. Fig. 3 shows the species yields for soot and CO from an upholstered furniture experiment showing how the species production changes as a function of time. Clearly there is a significant need for more comprehensive species production data.

Table 1. Species yields and effective heat of combustion for polyurethane foam and timber taken from a number of sources in the literature.

Description	**Soot yield**	**CO yield**	**ΔH_c**	**Source**
Polyurethane foam				
Flexible PU foam (GM21)	0.131	0.01	26.2	[23]
Flexible PU foam (GM23)	0.227	0.031	27.2	[23]
Flexible PU foam (GM25)	0.194	0.028	24.6	[23]
Flexible PU foam (GM27)	0.198	0.042	23.2	[23]
Flexible PU foam	<0.01–0.035	NR	NR	[24]
Flexible PU foam (non fire retardant)	0.036			[25]
Flexible PU foam (fire retardant)	0.067			[25]
PU (Flaming)	0.09	NR	NR	[26]
PU (Pyrolysis)	0.019–0.06	NR	NR	[26]
Flexible PU foams	0.07	0.028	17.6	[27]
PU foam	0.054	NR	18.4	[27]
Flexible PU	<0.01–0.23	0.042	19.0	[28]
Timber				
Douglas fir	NR	0.004	16.4	[23]
Douglas fir	<0.01–0.025	NR	NR	[24]
Douglas fir (flaming)	<0.01–0.035	NR	NR	[26]
Douglas fir (pyrolysis)	0.03–0.17	NR	NR	[26]
Douglas fir	0.01	NR	14.7	[27]
Hemlock	0.015	NR	13.3	[23]
Hemlock	0.015	NR	13.3	[27]
Pine	NR	0.004	17.9	[23]
Red oak	0.015	0.004	17.1	[23]
Timber	<0.01–0.025	0.02	13.0	[28]

NR – not reported



(a)

(b)

Fig. 3. Upholstered furniture fire experiment time-dependent: (a) soot yield; (b) CO yield.

REQUIRED SAFE EGRESS TIME (RSET)

Current Methodology

In simple terms the ASET is based on predicting the response of the fire in the building and the RSET is based on predicting the response of the occupants. RSET is the calculated time available between ignition of the design fire and the time when the occupants in the specified room are able to reach a place of safety. The RSET can be calculated using a number of sophisticated computer models or a simple hydraulic model for evacuation [29]. For this discussion the RSET will be simply described by the following relationship:

$$\text{RSET} = \Delta t_{det} + \Delta t_{alarm} + \Delta t_{pre} + (\Delta t_{travel}) \quad (3)$$

For this discussion the following simple descriptions are adopted for the quantities used in Eq. 3. The detection time (Δt_{det}) is the time from ignition to detection by an automatic system or time for occupants to detect the fire's cues, the alarm time (Δt_{alarm}) is the time from detection to the general alarm, the pre-movement (Δt_{pre}) is the time from alarm to the time when occupants start to egress the building, and the travel time (Δt_{travel}) is the time it takes for the occupants to travel from their location in the building to a safe place. The travel time commonly comprises two parts, the walking time and the flow time. The walking time is based on the speed that the occupants are expected to walk when egressing. The flow time is the time it takes for the occupants to flow through the exit, which includes flows through a doorway or down stairs. This can also include the time an occupant is in a queue waiting to evacuate a space.

For a detailed description on how to determine the values listed above the reader is directed to [29]. In an RSET analysis the detection time is calculated using a deterministic model to estimate the time a detection device will take to activate. Originally this was carried out using the program DETACT, which estimated the detection time based on the ceiling jet temperature and velocity and the response time index (RTI) of the detection device. However as our understanding of detection theory has improved, so have the models for predicting the detection time. The reader should consult [30] for more detail on the detection theory.

The alarm time and pre-movement times should be agreed upon as part of the fire engineering brief (FEB) process before calculating the RSET. Proulx has carried out a number of studies quantifying the evacuation times from both trial evacuations and actual fires that are summarized in [31]. Unfortunately researchers in the area of human behavior are reluctant to suggest numbers for the pre-movement times due to the limited research in this area. However, PD7974-6:2004 [3] does address the pre-movement times for occupants and gives guidance for estimating the pre-movement times. The suggested times are based on: occupancy classification, alert status of the occupants (awake or asleep), familiarity with the building, level of management, and type of alarm signal.

The values given in Columns 2 and 3 in Table 2 give the time from alarm to the movement of the first few occupants and the distribution times for the populations of occupants to start their evacuation. For additional details regarding the values given in Table 2 the reader should consult PD7974-6:2004 [3]. The pre-movement times shown in Table 2 demonstrate the wide range of values that might be expected in a building. Clearly the biggest influence is the level of management within the building. For example, for office buildings the values range from 0.5 to >15 min for first occupants to start moving based on the quality of the management. The alarm type dependence is less significant than management but is a major factor when only a manual alarm is available. For complex buildings a fixed amount of time is added to the pre-movement times ranging from 0.2 to 1.0 min. Admittedly the values reported in Table 2 are based on a very limited set of research.

Research Needs in RSET Analysis

Although there are a number of areas of active research on the topic of human behavior and movement, the greatest uncertainty is in the area of occupant response. Most of the studies carried out on occupant response time have been for unannounced trial evacuations, which may be applicable to occupants who are outside the room of fire origin; they may have limited application when the occupants are near the fire and are exposed to other cues from the fire. With the advent of video cameras on most cell phones and closed-circuit security cameras, future studies are likely to benefit from video taken during actual events such as the TV news footage taken during the Station Nightclub fire [32]. Analysis of such video footage will prove very useful in understanding occupant response and many other human factors in future evacuation and occupant response studies.

Table 2. Suggested pre-movement times from PD7974-6:2004, for a more comprehensive discussion of the premovement times the reader should consult Ref. [3].

Scenario category and modifier	**First occupants $\Delta t_{pre\ (1st\ \%)}$ (min)**	**Occupant distribution $\Delta t_{pre\ (99th\ \%)}$[a] (min)**
A: Awake and familiar (office or industrial)		
M1 B1 – B2 A1 – A2	0.5	1.0
M2 B1 – B2 A1 – A2	1	2
M3 B1 – B2 A1 – A3	*>15*	*>15*
B: Awake and unfamiliar (shop, restaurant, circulation space)		
M1 B1 A1 – A2	0.5	2
M2 B1 A1 – A2	1.0	3
M3 B1 A1 – A3	*>15*	*>15*
Ci: Sleeping and familiar (e.g. dwellings – individual occupancy)		
M2 B1 A1	*5*	*5*
M3 B1 A3	*10*	*>20*
Cii: Managed occupancy (e.g. serviced apartments, halls of residence)		
M1 B2 A1 – A2	*10*	*20*
M2 B2 A1 – A2	*15*	*25*
M3 B2 A1 – A3	*>20*	*>20*
Ciii: Sleeping and unfamiliar (e.g. hotel, boarding house)		
M1 B2 A1 – A2	*15*	*15*
M2 B2 A1 – A2	*20*	*20*
M3 B2 A1 – A3	*>20*	*>20*
D: Medical care.		
Awake and unfamiliar (e.g. day centre, clinic, surgery, dentist)		
M1 B1 A1 – A2	0.5	2
M2 B1 A1 – A2	1.0	3
M3 B1 A1 – A3	*>15*	*>15*
Sleeping and unfamiliar (e.g. hospital ward, nursing home)		
M1 B2 A1 – A2	5[b]	10[b]
M2 B2 A1 – A2	10[b]	20[b]
M3 B2 A1 – A3	*>10*[b]	*>20*[b]
E: Transportation. Awake and unfamiliar (e.g. airports, bus station)		
M1 B3 A1 – A2	1.5	4
M2 B3 A1 – A2	2.0	5
M3 B3 A1 – A3	*>15*	*>15*

[a] Total pre-movement time = $\Delta t_{pre\ (1st\ \%)} + \Delta t_{pre\ (99th\ \%)}$. *Italics* indicates greater uncertainty.

[b] These times depend upon the presence of sufficient staff to assist evacuation of handicapped occupants.

Management level

M1-occupants (staff and residents) should be trained to a high level of fire safety management

M2-similar to M1 but lower staff ratio and floor wardens not always present

M3-basic management with minimum fire safety management

Alarm level

A1-automatic detection throughout the building activating an immediate general alarm to all occupants

A2-automatic detection throughout the building providing a pre-alarm to management or security with a manually activated general alarm

A3-local automatic detection and alarm only near location of the fire or no automatic detection with manually activated general alarm

Building complexity

B1-simple rectangular single story building with one or few enclosures and simple layout

B2-simple multi-enclosure (usually multi-story) building and simple internal layout

B3- Large complex building where occupants may have wayfinding difficulties.

PERFORMANCE CRITERIA

The performance criteria can be as challenging as the design fire scenarios and design fires themselves. The appropriate performance criteria are dependent on the particular fire scenario and the portion of the design being evaluated. For building-to-building fire spread the performance criteria could be an allowable radiative heat flux or surface temperature on the adjacent building or boundary, for structural performance it could be a prescribed time in a specific standard fire test, for surface finish it could be a performance in a standard flame spread test. Quantifying the performance is much more challenging when predicting the impact of the fire on the occupants necessary for ASET versus RSET analysis. The fire impact on life safety is commonly broken down into four categories; thermal effects, narcotic gas effects, irritant gas effect and visibility. The most comprehensive review on the hazard to occupants from the fire gases is given by Purser in The SFPE Handbook of Fire Protection Engineering [33]. In this section, Purser gives a compendium of the available literature on the hazards that smoke poses to humans, and provides the engineering tools necessary to allow the designer to estimate the hazard that the smoke may have on egressing occupants. The assessment is usually in the form of the FED which is defined as the ratio of the exposure dose to the exposure dose necessary to produce incapacitation. The FED can be defined for asphyxiant toxicants, irritant gases, or radiative and convective heat exposure. For information on calculating the hazard for occupants posed by the smoke and heat the reader is directed to Refs. [33,34,35].

Ultimately the performance criteria must be selected for life safety. Although an FED of 1 is considered to be the point at which a person might be expected to be incapacitated, it is considered prudent, for two primary reasons, to use a value less than one for ‘conservatism’. Firstly, the uncertainty in calculations is high because of the limited amount of data available for comparison. The data used to develop the relationships are based on both human and animal research. To further refine the results, additional experiments would be necessary. However, exposing humans to dangerous toxic species is considered unethical and is not expected to ever be available. The second reason is that the data used was for young healthy adult humans and animals which represent the least vulnerable population. Certain subpopulations such as the elderly and the young are expected to be more vulnerable to the effects of fire and must be considered in design. Thus documents such as PD 7974-6:2004 [3] recommend the use of the FED < 0.3 as the acceptance criteria and visibility of 10 m. In cases where the occupants are considered to be a vulnerable subpopulation, the FED may be set even lower.

A CASE STUDY IN DEFINING THE INPUT FOR ASET VERSUS RSET ANALYSIS

Since August 2006 the New Zealand Department of Building and Housing (DBH) has been developing a new methodology to demonstrate compliance with the fire safety requirements of the New Zealand Building Code (NZBC), specifically the ‘C’ clauses. This work was identified as necessary after a comprehensive review of the existing building code. One of the key outcomes of the review was that the public feels that the existing code provides an acceptable level of safety. The NZBC will maintain its performance basis for fire safety but inputs for performance-based designs will be predetermined. This approach still permits flexibility and innovation in design, but ensures consistency between designs for very similar uses. This provides a mechanism for the regulator to exercise control over the level of fire safety that must be achieved in buildings, without having to go through a formal process to calculate the expected fire losses on a building-by-building basis. These inputs are analogous to wind, earthquake, snow loads etc. given in a loadings code for structural design. At the time of this paper (February 2011), the verification method has been drafted and has gone through a public consultation cycle, and is expected to be published by the end of 2011 following revision and ministerial approval. The design fire scenarios, design fires, pre-movement times, and acceptance criteria are briefly discussed below as an example of where this author believes the future of PBD should lead.

#	Description	Performance objective	Design event	Expected methodology
1	These fires are intended to represent a credible worst case scenario that will challenge the fire protection features of the building.	Provide a tenable environment for occupants in the event of fire while they egress to a safe place.	Design fires are characterized with t-squared rate of heat release, peak rate of heat release, and fire load energy density (FLED). Design values for yields are specified for CO, CO_2 and soot/smoke.	Calculations of the fire environment in the escape routes that will be evaluated using the tenability criteria. Modelling applies to: • any room/space > 200 m²; and • any room/space with occupant load >150 persons; and • any room > 2 m² (other than toilet facilities) connected to, but not fire separated, from an exitway.
2	Fire is located near the primary escape route or exit that prevents occupants from leaving the building by that route. Fire originating within an exitway may be the result of a deliberately lit fire.	Provide a viable escape route from the building for occupants in the event of fire, i.e. provide at least two exits of equal size.	Fire blocking exit in open or safe path. Fire characteristics are not required since fire is assumed to physically block the exit. (The fire is assumed to be of a size that would prevent use of the exit).	Where required, provide alternative escape routes that are tenable. Analysis not required. This fire scenario applies to escape routes in: • an open path or horizontal safe path serving more than 50 people; and • a vertical safe path serving more than 150 people, or if the building is sprinkler protected, 250 people. Escape routes serving less than 50 persons will be permitted to have a single exit.
3	A fire starting in an unoccupied space may grow to a significant size undetected and spread to other areas with the greatest number of occupants.	Maintain tenable conditions in escape routes until occupants have evacuated. Protect against fire spread that could compromise the retreat of firefighters.	Use fire characteristics from Scenario 1 for the applicable occupancy.	Include fire separations or fire suppression to confine the fire to the room of origin. Include automatic detection to provide early warning of the fire in the unoccupied space. Carry out tenability analysis of escape routes if fire is able to spread into the occupied space. Apply to buildings with rooms or spaces that have an occupant load of 50 or more people.
4	A fire that starts in a concealed space could develop undetected and spread to endanger a large number of occupants in a room.	Maintain tenable conditions in escape routes until occupants have evacuated. Protect against fire spread that could compromise the retreat of firefighters.	Currently unable to identify suitable quantitative. Expect traditional solutions would apply, i.e. containment, detection or suppression.	Provide fire separations or suppression to confine fire to concealed space or provide automatic detection for early warning. This fire scenario applies to buildings with rooms holding more than 50 occupants. This scenario does not apply if the concealed space has no combustibles and is less than 0.8 m deep.

#	**Description**	**Performance objective**	**Design event**	**Expected methodology**
5	Smouldering fire that causes a threat to sleeping occupants.	Maintain tenable conditions on escape routes.	Refer to fire characteristics for a smouldering fire.	Provide automatic smoke detection in sleeping rooms and further analysis is not required. Apply to buildings with sleeping occupants.
6	A large fire within a building may spread to neighbouring buildings as a result of heat transfer.	Prevent fire spread to other property.	Emitted radiation flux from unprotected areas in external walls : 88 kW/m² for FLED = 400 MJ/m² 108 kW/m² for FLED = 800 MJ/m²; 152 kW/m² for FLED > 1200 MJ/m².	• Unprotected areas can be calculated using the given emitted and maximum permitted received radiation levels, boundary distances and configuration factors. Does not apply to buildings with automatic sprinkler system with a Class A water supply. • Fire tests of external cladding systems using the cone calorimeter apparatus to demonstrate resistance to ignition.
7	A fire source adjacent to an external wall such as a fire plume emerging from a window, or a fire source in close to façade that could ignite and spread fire vertically. a) External vertical fire spread via the façade materials. b) Window fire spreading through openings above.	• Prevent fire spread to other properties and spaces where people sleep (in the same building) and maintain tenable conditions on escape routes until the occupants have evacuated. • Protect against external vertical fire spread that could threaten firefighters.	For 7a: • Radiant flux of 50 kW/m² on the façade for 15 min. (for PG II and PG III). • Radiant flux of 90 kW/m² on the façade for 15 min. (for PG IV). For 7b: • Window plume projecting from opening in external wall, with characteristics from design fire for Scenario 1.	1. Follow C/AS1 and use: a. Large or medium-scale ‘façade type’ fire tests (e.g. NFPA 285, ISO 13785). b. Small-scale testing using ISO 5660 (cone calorimeter) where appropriate. 2. Use non-combustible materials (AS 1530.1 or ISO 1182). 3. Validated flame spread models (if available). 4. Construction features such as ‘aprons’ and/or ‘spandrels’ or ‘sprinklers’ could be used to meet performance criteria for 7b. This fire scenario applies to: • Buildings where upper floors contain sleeping occupancies or ‘other properties’. • Buildings of height >10 m.
8	A flaming fire source located in a wall-corner junction that potentially ignites room surface lining materials and subsequently leads to untenable conditions on an escape route.	• Tenable conditions on escape routes shall be maintained while occupants evacuate. Protect against rapid fire spread that could compromise the retreat of firefighters.	Fire source of 100 kW in contact with a wall-corner element for 10 min followed by 300 kW for 10 min in accordance with ISO 9705.	1. ISO 9705 room corner fire. 2. ISO 5660 cone calorimeter test at 50 kW/m² (used with a correlation to an ISO 9705 full-scale result). 3. Use non-combustible materials to AS 1530.1 or ISO 1182. Use calculations from validated flame spread models (if available for the material and configuration of interest).

#	Description	Performance objective	Design event	Expected methodology
9	Provide firefighters with the means to fight the fire with an element of safety.	Allow officer in charge to make risk-informed judgement for firefighting and rescue operations: • Information must be available to the crew on arrival to enable them to rapidly size-up. • Access to all floors of the building must provide firefighter protection. • Firefighting water must be available in the near fire.	Firefighter tenability must be established for large buildings (>1500 m^2) with a fire load greater than 1500 MJ/m^2, where fire growth rate is very rapid, or for unsprinklered building layouts where the distance from the safe path access to any point on a floor exceeds 75 m. The firefighting design fire is 50 MW.	**1. Features that facilitate rapid size-up of the situation:** • Fire detection system; • Alarm panel location and information; • Firefighter control of building fire safety systems; • Limitation of fire size by sprinklers or fire-cell size. **2. Features that facilitate safe access for rescue and firefighting:** • Firefighter access around building; • Sprinklers in buildings higher than fire service ladder appliances; • Access through tall buildings; • Protected from structural collapse. **3. Features that facilitate adequate firefighting water:** • External hydrants plus fire appliance access to building; • Internal risers, hydrants and hose reels; • Sprinklers.
10	Test the robustness of the design by considering the design fire with each key fire safety system rendered ineffective	Provide a tenable environment for occupants in the event of fire while they escape to a safe place.	Design event is the same as Scenario 1 above.	Calculations of the fire environment in the escape routes that will be evaluated with one of the key fire safety systems rendered ineffective. Only the FED (CO) criterion is to be met.

Design Fires

Quantifying the design fire is one of the most challenging requirements for PBD. Resolving the issue of defining the design fire has resulted in some reflection on the existing compliance documents which have been considered to provide a societal accepted level of safety. Indeed, if the design fires required for use in PBD are significantly more severe than the inherent fires within the compliance documents [36], then there is a disincentive for PBD that would suppress innovation in building design. Thus choosing an appropriately rigorous design fire to provide an acceptable level of safety without being too onerous to stifle PBD requires a great deal of effort. Ultimately the following design fire was chosen (the few exceptional cases are discussed below):

- For all buildings except for the buildings explicitly discussed below, the fire is assumed to grow as a fast t^2 fire up to flashover, and is then limited by the available ventilation assuming all windows are broken out.
- For sprinklered buildings the fire is assumed to be controlled, i.e. constant heat release rate, after the sprinkler activates based on RTI and activation temperature.
- Species yield for soot (Y_{soot}) is equal to 0.07 kg/kg_{fuel}.
- Species yield for carbon monoxide (Y_{CO}) is equal to 0.04 kg/kg_{fuel}.
- Net heat of combustion (ΔH_c) 20 MJ/kg
- Radiative fraction from fire 0.35

Exceptions to the fast t^2 fire:

Building use	Fire growth rate	Species
Car parks	$0.0111\ t^2$	$Y_{soot} = 0.07$, $Y_{CO} = 0.04$ $\Delta H_c = 20$ MJ/kg
Rack storage < 6 m	$0.178\ t^2$	$Y_{soot} = 0.07$, $Y_{CO} = 0.04$ $\Delta H_c = 20$ MJ/kg
Rack storage > 6 m	$0.00068\ t^3\ H$	$Y_{soot} = 0.07$, $Y_{CO} = 0.04$ $\Delta H_c = 15$ MJ/kg

Performance Criteria

The performance criteria have been taken primarily from PD7974-6:2004 [3]. These values are consistent with the values found in the literature. Two exceptions are applied to the criteria: the first is the relaxed values allowed for sprinklered buildings. In New Zealand sprinkler systems have a rigorous inspection and maintenance regime that helps to ensure that the system will function as designed when required. In addition the current level of modeling does not adequately take into account the positive effect sprinklers can have so the relaxation of the performance criteria is necessary to promote the use of sprinklers. The second relaxation is that the performance criteria are not assessed within the household unit of origin.

Two performance criteria are suggested: the simple criteria are used when the smoke layer is not expected to impact the egressing occupants and this greatly simplifies the analysis. The second more detailed criteria are used whenever the occupants are expected to have to egress through the smoke.

Occupant Life Safety - Simple Criteria

The simple criteria are used when the smoke layer is not expected to reach the occupants.

1. minimum clear smoke layer height of 2.5 m
2. maximum upper layer temperature of 200 ºC

Obviously, this method will not be suitable for spaces with low ceilings or where a distinct layer interface cannot be determined.

Occupant Life Safety - Detailed Criteria

The detailed criteria are applied when the occupants are assumed to be egressing through the smoke. Three criteria, all must be achieved. Calculations should be in accordance with ISO/TS 13571 [35]. FEDs and visibility may be determined at a height of 2.0 m above floor level using upper/lower layer properties as applicable, or else can be based on upper layer properties alone.

1. FED for narcotic (toxic) gases. This accounts for the cumulative effects of CO, O_2 depletion and CO_2 effects on the respiration rate. FED ≤ 0.3 (suitable for most general occupancies).
2. FED for radiant and convective heat. This accounts for cumulative exposure to skin to radiant heat (2nd degree burns) and to convective heat from air. FED ≤ 0.3 (suitable for most general occupancies).
3. Visibility not less than 5 m, for rooms/spaces ≤ 100 m².
   Visibility not less than 10 m, for rooms/spaces > 100 m².
4. For sprinklered buildings (System installed according to NZS4541 [37] or NZS4515 [38],
   Visibility and FED thermal criteria do not apply.
   FED narcotic < 0.3.
5. Within the household unit of fire origin, tenability criteria are not assessed.

Pre-Movement Times

In New Zealand, there exist the Evacuation Regulations which require most commercial buildings open to the public to have an approved evacuation scheme. As a result there is a widespread culture of evacuating a building when the fire alarm sounds. Therefore shorter times than are typically found in the literature have been suggested:

Table 3. Pre-movement times for proposed in the New Zealand performance-based design framework

Description of building use	**Pre-movement time (s)**		
	Fire cell of origin	Elsewhere	PD7974 (1^{st} %) 99^{th} %
Buildings where the occupants are considered awake, alert and familiar with the building, i.e.: offices, warehouse etc.	30	60	(30) 60
Buildings where occupants are considered awake, alert and unfamiliar with the building, i.e.: retail, exhibition, restaurants:			
Standard alarm	60	120	-
Voice alarm	30	60	(30) 120
Buildings where the occupants are considered sleeping and familiar with the building, such as sleeping residential.	60	300	(300) 300
Buildings where the occupants are considered sleeping and unfamiliar with the building, i.e.: sleeping accommodation:			
Standard alarm	60	600	-
Voice alarm	60	300	(900) 900
Buildings where the occupants are considered awake and under the care of trained staff i.e.: day care, dental office, clinic.	60	120	(30) 120
Buildings where the occupants are considered to be asleep, under the care of trained staff, i.e.: hospitals and rest homes.	300	1800	(300) 600
Spaces which have only focused activities such as cinemas, theatres, stadiums, etc.	When fire reaches 0.5 MW		No equivalent

CONCLUSIONS

Performance-based design can provide for cost-effective and innovative solutions to fire safety challenges yet the analysis required for PBD is complex and the required inputs can be difficult to obtain. Unfortunately, the available guidance is almost exclusively qualitative in nature. As demonstrated in this paper, the fire engineering community is reluctant to provide quantitative guidance, preferring to leave such decisions up to the designers. In most jurisdictions, the parameters used within a performance-based design such as the design scenarios, design fires and acceptance criteria are suggested by the designer with the approval of the AHJ, which can lead to inconsistent levels of safety being achieved for the design of similar buildings. If performance-based design is to continue to be preferred over prescriptive design then it is time for the fire engineering community to provide quantitative guidance to designers for use in the PBD.

Based on New Zealand's experience, the consequences of the current system, that is, of having the designer recommend the input parameters and acceptance criteria with approval of the AHJ include [39]:

- inefficient consenting process as designers and AHJs negotiate what constitutes compliance;
- major delays in the construction and occupation of buildings;
- increased construction and capital costs for developers;
- pressure on the appeal process under the Building Act 2004;
- stifled innovation and limited design options.

In response to these concerns, the Department of Building and Housing is developing a new verification method that is intended to set out a clear method for PBD to comply with the NZBC, thereby removing the existing scope for interpretation and dispute. The intent of specifying the design fire scenarios, design fires, pre-movement times and acceptance criteria is to lead to greater consistency of fire design, greater certainty and reduced compliance costs for the building industry, and a design process that is more efficient.

REFERENCES

[1] Custer, R.L.P. and Meacham, B.J., *Introduction to Performance-Based Fire Safety*, Society of Fire Protection Engineers and National Fire Protection Association, Quincy, MA, USA, 1997.

[2] Hadjisophocleous, G.V. and Mehaffey, J., "Fire Scenarios", *The SFPE Handbook for Fire Protection Engineering (4th ed.),* Section 5 Chapter 11, 2008.

[3] PD7974-6:2004 *The application of fire safety engineering principles to fire safety design of buildings Part 6: Human factors: Life Safety strategies – Occupant evacuation, behaviour and condition,* British Standards, 2004.

[4] NFPA101, *Life Safety Code*, National Fire Protection Association, Quincy, MA, USA, 2009.

[5] *SFPE Guide to Performance-Based Fire Protection (2nd ed.)*, Society of Fire Protection Engineers and National Fire Protection Association, Quincy, MA, USA, 2007.

[6] ISO/TS16733 *Fire safety engineering – Selection of design fire scenarios and design fires*, International Organization for Standardization, 2006.

[7] NFPA5000, *Building Construction and Safety Code*, National Fire Protection Association, 2009.

[8] *International Fire Engineering Guidelines*, Australian Building Codes Board, Australia, 2005.

[9] Tubbs, B., "SFPE Technical Priorities for the Future", (2008) *Fire Protection Engineering*, Society of Fire Protection Engineers, 3rd Quarter, http://www.fpemag.com/archives/article.asp?issue_id=10&i=362.

[10] Babrauskas, V. and Peacock, R.D., (1992) Heat Release Rate: The Single Most Important Variable in Fire Hazard, Fire Safety Journal, 18: 255-272. http://dx.doi.org/10.1016/0379-7112(92)90019-9

[11] NPFA72 *National Fire Alarm Code,* National Fire Protection Association, Quincy, MA, USA, 2002.

[12] NFPA204 *Guide to Smoke and Heat Venting*, National Fire Protection Association, Quincy, MA, USA, 2007.

[13] Babrauskas, V., (1996) "Fire Modeling Tools for FSE: Are They Good Enough?" Journal of Fire Engineering, 8(2): 87-96. http://dx.doi.org/10.1177%2F104239159600800203

[14] Kawagoe, K., "Fire Behaviour in Rooms", Report of the Building Research Institute, No. 27, Ibaraki-ken, Japan, 1958.

[15] Fleischmann, C.M. and Parkes, A.R., 1997. Effects of Ventilation on the Compartment Enhanced Mass Loss Rate. Fire Safety Science 5: 415-426. http://dx.doi.org/10.3801/IAFSS.FSS.5-415

[16] Young, E.A., "Standardising Design Fires For Residential and Apartment Buildings: Upholstered Furniture Fires", Masters Thesis, University of Canterbury, 2007.

[17] Sundstorm, B., *Fire Safety of Upholstered Furniture – the final report on the CBUF research programme*, Interscience Communication Limited, London, UK, 1995.

[18] Enright, P.A., "Heat Release and the Combustion Behaviour of Upholstered Furniture", PhD Thesis, University of Canterbury, 1999.

[19] Denize, H., "The Combustion Behaviour of Upholstered Furniture Materials in New Zealand", Masters Thesis, University of Canterbury, 2000.

[20] Hill, G., "Burning Behaviour of Upholstered Furniture", Masters Thesis, University of Canterbury, 2004.

[21] Technical Bulletin 133, *Flammability Test Procedure for Seating Furniture in for Use in Public Occupancies*, California Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, USA, 1991.

[22] Baker, G.B. and Wade, C.A., “Development of the Probabilistic Design and Analysis Tools for Performance-Based Design Fire Safety Engineering”, Proceedings of the 2009 International Symposium on Fire Science and Fire Protection Engineering, Beijing, China.

[23] Tewarson, A., *“*Generation of Heat and Gaseous Liquid and Solid Products in Fires”, *The SFPE Handbook for Fire Protection Engineering (4th ed),* Section 3 Chapter 13*,* National Fire Protection Association, Quincy, MA, USA, 2008.

[24] Mulholland, G.W., “Smoke Production and Properties", *The SFPE Handbook for Fire Protection Engineering (4th ed.),* Section 3 Chapter 13*,* National Fire Protection Association, Quincy, MA, USA, 2008.

[25] Krasny, J.F., Parker, W.J. and Babrauskas, V., *Fire Behavior of Upholstered Furniture and Mattresses*, Noyes Publications, Norwich, NY, USA, 2001.

[26] Whiteley, R.H., “Smoke Production, Properties and Measurements”*, Hazards of Combustion Products,* Interscience Communications, London, UK, 2008.

[27] Tewarson, A., “Flammability of Polymers”, *Plastics and the Environment,* Chapter 11, John Wiley & Sons, Chichester, 2003.

[28] CIBSE Guide E, “Fire engineering”, The Chartered Institution of Building Services Engineers, London, UK, 1997.

[29] Gwynne, S.N.V. and Rosenbaum, E.R., “Employing the Hydraulic Model in Assessing Emergency Movement”, Chapter 13 Section 3, *The SFPE Handbook of Fire Protection Engineering (4th ed.),* National Fire Protection Association, Quincy, MA, USA 2008.

[30] Custer, R.L.P., Meacham, B.J. and Schifiliti, R.P., “Design of Detection Systems”, *The SFPE Handbook for Fire Protection Engineering (4th ed.),* Section 4 Chapter 1, National Fire Protection Association, Quincy, MA, USA 2008.

[31] Proulx, G., “Evacuation Time”, *The SFPE Handbook for Fire Protection Engineering (4th ed),* Section 4 Chapter 1, National Fire Protection Association, Quincy, MA, USA, 2008.

[32] Duval, R.P., “NFPA Case Study: Nightclub Fires”, National Fire Protection Association, Fire Investigation Department, Quincy, MA, 2006.

[33] Purser, D.A., “Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat”, *The SFPE Handbook for Fire Protection Engineering (4th ed),* Section 2 Chapter 6, National Fire Protection Association, Quincy, MA, USA, 2008.

[34] Gann, R.G. and Bryner, N.P., “Combustion Products and Their Effects on Life Safety”, *Fire Protection Handbook (20th ed.),* Section 6 Chapter 2, 2008.

[35] ISO/TS113571, *Life-threatening components of fire- Guidelines for the estimation of time available for escape using fire data,* International Organization for Standardization, 2007.

[36] Compliance Document for New Zealand Building Code Clauses C1, C2, C3, C4, Fire Safety, Department of Building and Housing, Wellington, NZ, 2008

[37] NZS4541:2007, *Automatic Fire Sprinkler Systems*, Standards New Zealand, 2007.

[38] NZS4515:2003, *Fire Sprinkler Systems for Residential Occupancies*, Standards New Zealand, 2003.

[39] “Proposed changes to Building Code requirements and associated documents for protection from fire”, Department of Building and Housing, Wellington, NZ, 2010.