

Tenability criteria for design of smoke hazard management systems

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ABSTRACT

In the design of smoke hazard management systems for buildings, the key objective is to ensure that the occupants have sufficient time to safely evacuate before the egress routes become untenable from the effects of smoke from a fire. Unfortunately, the Building Code of Australia (BCA) does not provide specific guidance on setting the tenability criteria. Furthermore, there are also no set values for tenability criteria that are universally accepted.

This paper outlines the smoke hazards and the experimental basis for tolerance thresholds to smoke exposures. Criteria are derived for design and evaluation of fire hazard management systems to satisfy the requirements of the BCA — to ensure effective evacuation of the building occupants. The criteria are generally conservative and lead to designs that err on the safe side.

INTRODUCTION

The main objective of smoke hazard management in buildings is to enable the occupants to move to a place of safety before the evacuation routes become untenable due to smoke. This objective is iterated as a Functional Statement in Section E2 Smoke Hazards Management of the Building Code of Australia (BCA) [1]:

EF2.1

A building is to be provided with safeguards so that –

- (a) occupants are warned of a fire in the building so that they may safely evacuate; and
- (b) occupants have time to safely evacuate before the environment in any evacuation route becomes **untenable** from the effects of fire.

The BCA further elaborates this in a Performance Requirement in the same section stating that:

EP2.2

- (a) In the event of a fire in a building the conditions in any evacuation route must be maintained for the period of time occupants take to evacuate the part of the building so that—
 - (i) the temperature will not endanger human life; and
 - (ii) the level of visibility will enable the evacuation route to be determined; and
 - (iii) the level of toxicity will not endanger human life.

Generally, the above Functional Statement and Performance Requirement are deemed to be satisfied when a building solution complies with the prescribed Deemed-to-Satisfy (DtS) Provisions of the BCA. This means that tenability in fire need not be explicitly evaluated, as opposed to an Alternative Solution where the fulfilment of the Performance Requirement must be demonstrated using a performance-based approach. However, an exception to DtS approach relates to the design of air-handling systems serving an atrium, where the BCA DtS Provisions also state that:

Specification 3.8, Clause 3.2

Mechanical air-handling systems serving an atrium must be designed to operate so that during a fire –

- (a) a tenable atmosphere is maintained in all paths of travel along balconies to required exits during the period of evacuation; and ...

In this DtS clause, a performance for tenability is specified, meaning that tenability of the building space must be evaluated in the design. Unfortunately, the BCA does not provide the necessary tenability criteria or provide specific guidance on setting the criteria — neither does the International Fire Engineering Guidelines [2], which is the guiding document for fire-engineering evaluation of Alternative Solutions.

There are various tenability criteria proposed overseas [3-6]. However, there are no single set that is universally accepted. Consequently, building designers in Australia must justify the criteria they use; and the relevant authorities must then judge their appropriateness when approving the design. Often disagreements and confusions arose due to difference in knowledge and understanding of the parties concerned regarding tenability in building fires.

In order to assist building designers better understand the subject, this paper outlines the background, design approaches and tenability criteria for design of smoke hazard management systems.

SMOKE HAZARDS AND TENABILITY LIMITS

In the event of a building fire, the occupants may be exposed to the fire and smoke. Statistical evidence shows that most fire deaths are not caused by direct contact with the fire, but by smoke inhalation. While a fire may be confined to a localised area in a building, the smoke produced will rise, forming a hot upper layer and may spread rapidly through the building. Hazards to the occupants include heat and toxic gases transported in the smoke and obscuration caused by the smoke (see Figure 1).

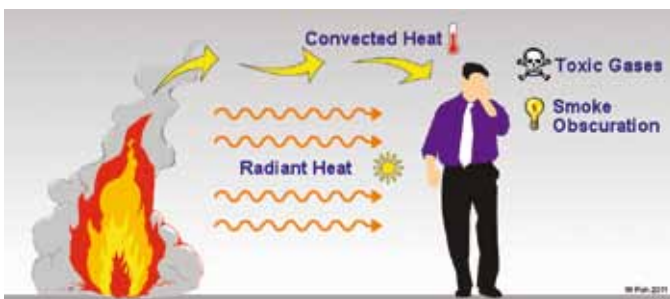


Figure 1: Hazards of Smoke from Building Fire

Exposure to toxic gases or heat may cause incapacitation (loss of consciousness); and severe exposure may cause death.

The International Fire Engineering Guideline [2] defines untenable conditions as: “environmental conditions associated with a fire in which human life is not sustainable”, in other words, conditions that cause death. For the purpose of design of smoke hazard management systems for safe evacuation, we consider that less severe conditions are more appropriate and tenability should be considered in terms of effective evacuation. Hence in the context of this paper, we consider tenability limits as exposure thresholds that cause incapacitation, injuries or ineffective evacuation movement.

Purser [7] gives a comprehensive review of the smoke hazards, including exposure thresholds that cause incapacitation and death. Some aspects of these are summarised below, with a focus on tenability limits for safe evacuation.

Convected heat

Prolonged exposure of more than 15 minutes to hot environments may cause heat stroke (hyperthermia). However, even for short durations, exposure to hot smoke at high temperatures may cause skin pain or skin and respiratory tract burns.

In 1960s and 1980s, tests were conducted by various researchers [15 – 17] where people were subjected to dry, heated environments at temperatures ranging from 110°C to 180°C to determine the tolerance time to convected heat. These were later compiled and a curve was fitted to the results to form the tolerance limits. The test results are shown in Figure 2 as circular dots together with fitted curve (red line).

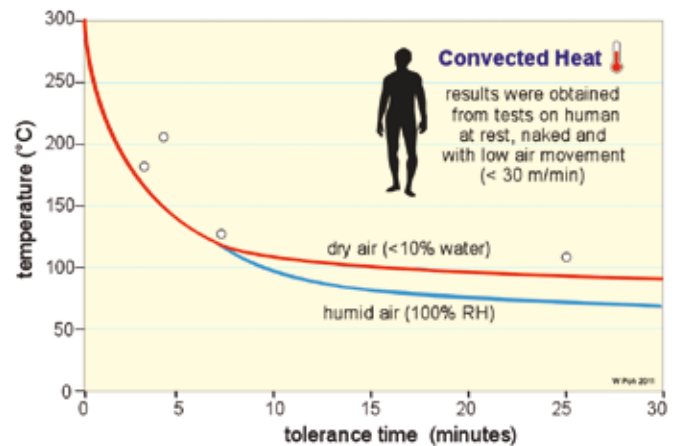


Figure 2: Tolerance to Convected Heat

Human tolerance to dry heat is largely attributed to human’s ability of evaporative cooling through sweating [19]. Increased humidity in the air may limit evaporation and hence lower the tolerance time. However, there appears to be a paucity of test data on human tolerance in humid environments to temperatures above 45°C. Nevertheless, a relationship is proposed in [18] for estimating tolerance time to convected heat in water saturated environments. This relationship is shown Figure 2 as the blue line. In most fire situations, the air environment is relatively dry and unlikely to be fully saturated with water. In order to account for mid-humidity conditions, empirical relationship, which lies approximately between the dry and humid lines, is also proposed in [7].

Radiant heat

Even without direct contact with the hot smoke, skin pain or burns could still occur when exposed to high levels of radiant heat from the fire or the smoke. In the periods from 1950s to early 1980s, various tests [15, 16, 21, 22] were conducted to determine the tolerance time for radiant heat exposure to levels ranging from 2.4 kW/m² to 23.5 kW/m². The tolerance limits were later compiled and a curve fitted through the test results. The test results are shown in Figure 3 as circular dots together with fitted curve.

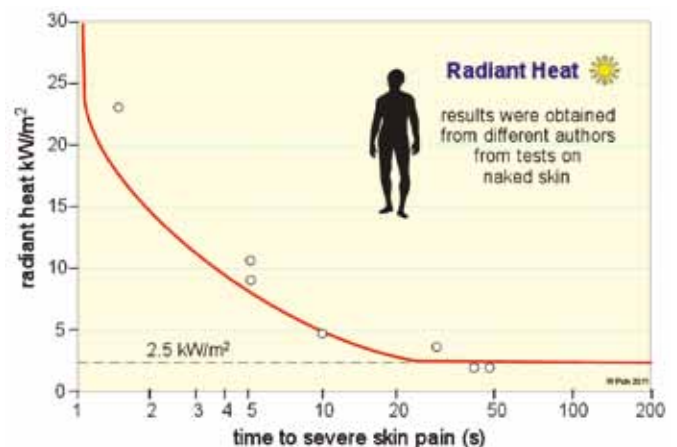


Figure 3: Tolerance to Radiant Heat

It is noted that the tolerance times in Figure 3 were obtained from radiant heat exposure to naked skin. It can be expected

that the limits are higher with the protection of clothing. For example, field tests [8] were conducted where the author, with the protection of light clothing, exposed himself to radiant heat flux of 5.0 kW/m² for 30 s without suffering skin pain or burns.

Toxic gases

In building fires, the most common asphyxiate is carbon monoxide (CO) and, to a lesser extent, hydrogen cyanide (HCN) which is more toxic. The exposure limits that cause incapacitation depend on the gas species, concentrations and durations of exposure. They were obtained from tests [7, 20] conducted on primates (juvenile baboons and cynomolgus monkeys) by subjecting them to various concentrations of CO and HCN. The results are shown Figure 4.

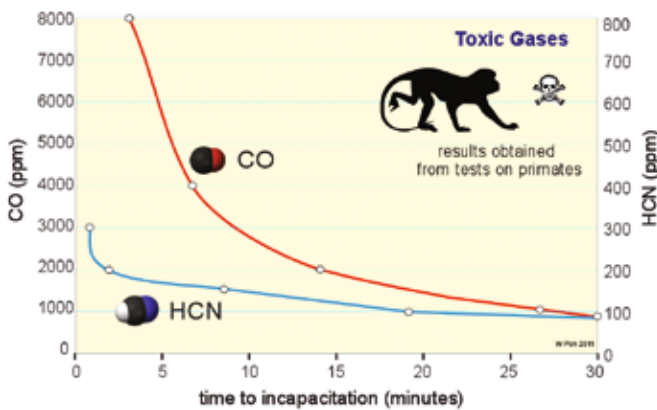


Figure 4: Tolerance to CO and HCN

It is assumed that these limits are the same for humans.

Loss of consciousness may also occur due to hypoxia at oxygen levels lower than 12%; or due to narcotic effects at carbon dioxide levels higher than 6%. However, it is considered that these conditions are unlikely to occur in building fire conditions [9, 10].

Smoke obscuration

Soot contained in smoke also obscures light and hence reduces visibility. Reduction in visibility is not directly life threatening such as heat or toxic gas exposure; however, it may reduce the walking speed of the occupants [11].

Combustion gases in the smoke may also cause irritation to the eyes. These include acid gases (HF, HCl, HBr, SO₂, NO_x) and organic irritant gases (acrolein, formaldehyde, crotonaldehyde). Their effects have a similar effect to reduced visibility (see Figure 5).

If the occupants are located at a significant distance from an exit and the visibility drops significantly, they may be unable to find their way out of the building. In either case, it may lead to an increased exposure time to heat and toxic gases which needs to be taken into account.

DESIGN APPROACHES

Generally speaking, there are two main approaches to the design of smoke hazard management systems. These are discussed below.

No smoke exposure

The first approach is to ensure that the occupants are not directly exposed to smoke — by keeping the smoke layer above

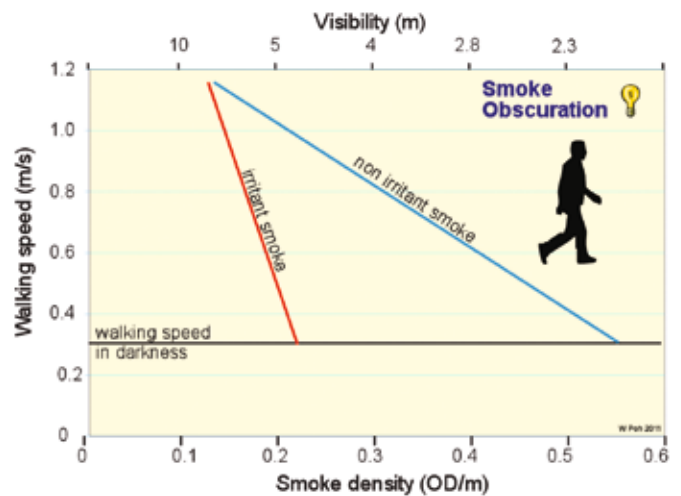


Figure 5: Walking Speed versus Visibility

the head height of the occupants. This height may be assumed to be 2.0m above the floor level, noting that the average heights of Australian adult males and females are 1.78m and 1.64m respectively [12]. This approach may be achieved by means of smoke exhaust, smoke venting, smoke containment or by ensuring that the occupants can quickly move out of the building (see Figure 6).



Figure 6: Occupants not Exposed to Smoke

The smoke exhaust systems prescribed by BCA Specification E2.2b are based on this approach, which requires the smoke layer to be maintained not less than 2.0m above the floor level.

Smoke exposure

In the second approach, it is assumed in the design that some of the occupants may need to move through tenable smoke environments to evacuate the building (see Figure 7).



Figure 7: Occupants Exposed to Smoke

TENABILITY CRITERIA

Irrespective of the design approach, the smoke hazard management system must be evaluated against a set of criteria to ensure safe evacuation of the occupants. This may be achieved by assuming a design fire and analysing the fire environments and occupant evacuation. The fire environments may be analysed using zone models such as CFAST [12] or computational fluid

dynamics (CFD) models such as FDS [14]. Movement of the occupants may be evaluated using a separate evacuation analysis.

The criteria to establish the tenability of the building space depend on the approach and the rigour of the analysis for the design. Three set of criteria are proposed in this paper to suit the design and evaluation approach. These are discussed below in order of increasing rigour of analyses.

No exposure

In situations where the occupants are not directly exposed to smoke, the tenability criteria are relatively simple (see Figure 8).

The first criterion is to ensure the smoke layer is located above the head height; and the second criterion is to ensure that the radiant heat from the fire and the hot smoke layer above does not exceed the skin pain threshold of 2.5 KW/m^2 (see Figure 3).

Since the smoke is located above the head height of the occupants, convected heat and toxic gases of the smoke need not be considered. However, it is noted that the radiant heat limit of 2.5 KW/m^2 may be reached when the hot layer temperature rises above 200°C .

This method has an advantage that the criteria and evaluation are relatively simple. The smoke layer height and radiant heat may be calculated using a zone or CFD model, and there is no need to evaluate the convected heat, toxic gases and obscuration of the smoke.



Figure 8: Tenability Criteria – No Exposure

Short exposure

For situations where the occupants may be exposed to smoke for a short duration of up to 10 minutes, a simple set of criteria as shown in Figure 9 may be used.

The criteria for convected heat and toxic gas exposures are obtained from tolerance limits in Figures 2–4, assuming a maximum 10-minute exposure. The air environment is conservatively assumed to be humid in establishing the tolerance to convective heat. The visibility limit of 10m is suitable for large

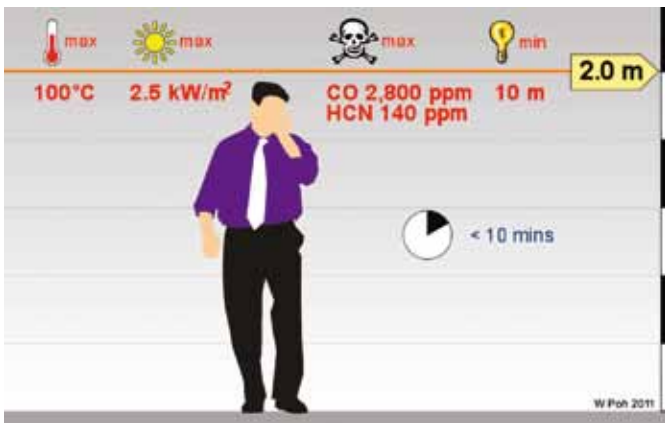


Figure 9: Tenability Criteria – Short Exposure

enclosures to assist occupant way finding. For small enclosure, a lower visibility limit of 5m may be used.

For the sake of convenience, the smoke hazards are evaluated at a height of 2.0m which, ironically, is above the head height of the occupants. This approach is conservative since the occupants are likely to be exposed to less severe conditions below the 2.0m height. Evaluation of the smoke hazards at a lower height, say 1.5m, which is commonly regarded as the breathing zone, is equally valid.

It is important to note that the convected heat and toxicity criteria are derived from tenability limits for constant exposures to the limiting values over the entire exposure period. For example, the criterion for convected heat represents the tolerance limit for a constant 10-minute exposure to 100°C. However, in a fire condition, the occupants are likely to be exposed to continual changing environments where the temperature increases with time until it reaches 100°C when it is considered untenable using this method. Such exposure is less severe than the constant exposure to 100°C over the entire period. From this viewpoint, this, and similarly the criteria for toxic gas exposure, are generally conservative.

The method described here requires each smoke hazard to be calculated for the period while the occupants evacuate the building. The criteria are relatively easy to apply, since each hazard needs to be checked independently against one corresponding limit.

General exposure

For situations where the occupants may be exposed to smoke for a longer duration of up to 30 minutes, a more general and rigorous analysis using Fractional Effective Dose (FED) method [7, 10] may be used to evaluate the tenability conditions.

The FED method involves the determination of exposure doses at regular discrete time increments and summing the exposure doses to get the cumulative dosage for the total period of exposure. The doses are calculated as a fraction of incapacitation dosage, and hence the maximum value of FED = 1.0 represents the state of incapacitation.

Heat exposure is calculated as a FED, taking into account the combined effects of convected and radiant heat. Toxic gas exposure is calculated as another FED, taking into account the combined effects of the relevant gases. The effects of varying O₂ and CO₂ may also be included in the calculation [7]. Using this method, the tenability criteria are shown in Figure 10.

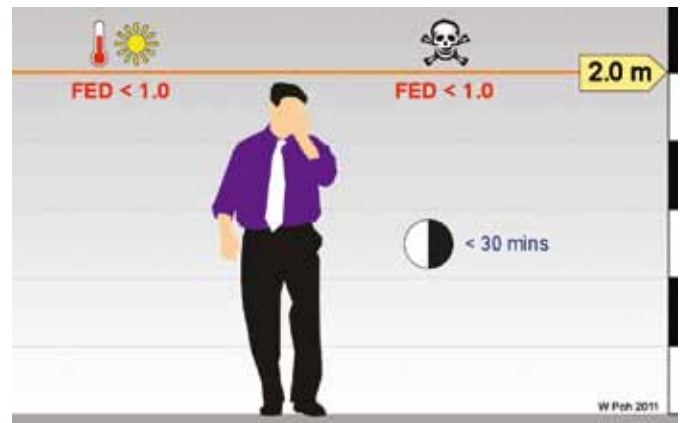


Figure 10: Tenability Criteria – General Exposure

Again, for the sake of convenience, the FEDs are evaluated at the height of 2.0m; although, as discussed in the previous section, they may be equally valid to evaluate them at a lower height of 1.5m.

The same approach may also be used to determine the fractional effective concentration (FEC) of combustion gases that cause irritation to the eyes and respiratory tracts, including acid gases (HF, HCl, HBr, SO₂, NO_x) and organic irritant gases (acrolein, formaldehyde, crotonaldehyde). The FEC may be used to modify the walking speed of the occupants, where FEC = 1.0 represents incapacitation or cessation of effective evacuation movement.

The FED method has the advantage that it takes into account the variation of the exposure environments with time and the combined effects of the exposures to various effects of the fire. It is particularly useful for situations where the occupants are exposed to low doses over a long period of time, or to high doses over a short period of time. This may lead to a more cost effective design of the smoke management system.

To date, this method has not been as widely used in design. However, it is envisaged it will gain popularity when more comprehensive FED calculations are incorporated into analysis programs such as CFAST and FDS.

CONCLUSIONS

This paper outlined the smoke hazards and the experimental basis that was used to derive the tenability limits for occupants to safely evacuate buildings in the event of a fire. Approaches for design and evaluation of smoke hazard management systems were also discussed.

Based on the tenability limits, criteria were given for different approaches for design and evaluation. These include:

No exposure:

- smoke layer height $\geq 2.0\text{m}$
- radiant heat $\leq 2.5\text{ kW/m}^2$

Short exposure (up to 10 minutes) – conditions at 2.0m height:

- radiant heat $\leq 2.5\text{ kW/m}^2$
- air temperature $\leq 100^\circ\text{C}$
- CO level $\leq 2,800\text{ ppm}$

- HCN \leq 140 ppm
- Visibility \geq 10 m (large enclosures); \geq 5 m (small enclosures)

General exposure (up to 30 minutes)

– conditions at 2.0m height:

- FED for toxic gases $<$ 1.0
- FED for heat $<$ 1.0

These criteria may be used for design of smoke hazard management systems to satisfy the requirements of the BCA. They are generally conservative and lead to designs that err on the safe side. ■

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Dr Weng Poh is an associate director and the head of the fire engineering group at Umow Lai. Throughout his career, Weng has completed numerous fire engineering projects. He has been closely involved in the development of methodology for fire safety designs of buildings in Australia and has published extensively in international journals, conferences and technical reports. Weng also gives lectures in postgraduate courses, aimed at training building practitioners in fire engineering design.