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Practice Note for Tenability Criteria in Building Fires

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1 Introduction

One of the main objectives of fire safety design of buildings is to enable the occupants to move to a place of safety before the evacuation routes become untenable. This objective is iterated as a Functional Statement in Section EF2 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 <u>untenable</u> 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 considered 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.

Unfortunately, the BCA does not provide the necessary tenability criteria or provide specific guidance on setting the acceptance 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, 4, 5, 6, 7]. However, there is 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.

To assist building designers in better understanding the subject, this practice note outlines the background, design approaches and tenability criteria for design of buildings for fire safety.

It is emphasised that this is a guidance document, for the purpose of enhancing consistency in the fire engineering industry. It is up to individual practitioners to determine to what extent (if at all) the guidance within this document is applied. For example, whilst this practice note includes guidance for fire brigade tenability, it is noted that the need to consider fire brigade tenability will be dependent on the needs of the project.

In this regard and generally throughout the application of the guidance within this practice note, practitioners are expected to exercise good 'Engineering Judgement – *"The process exercised by a professional who is qualified by way of education, experience and recognised skills to complement, supplement, accept or reject elements of a quantitative analysis"*[2].

2 Limitations of This Practice Note

This practice note has been prepared as a guide to practitioners on tenability criteria in building fires, for the purpose of enhancing consistency in the fire engineering industry. **The proposed methodology should not be claimed to be the only means of derivation**. This practice note should be used in conjunction with the International Fire Engineering Guidelines[2].

This practice note has been prepared under the regime of the Building Code of Australia and may not be 100% applicable under building regulatory regimes in other countries.

The data presented in this practice note was based on the information in fire engineering literature available to the working group at the time of preparation. It is the onus of the practitioners to make sure that the data are accurate, up to date, and applicable to specific projects with which the practitioners are involved.

Please also note the disclaimer in Section 7.

3 Background – Tenability Limits

3.1 Hazards of Building Fires

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).

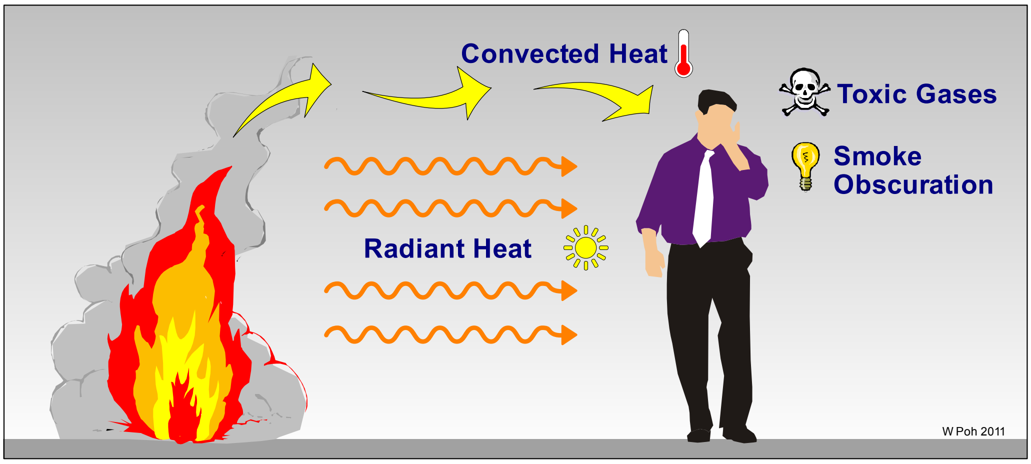

Figure 1: Hazards of Building Fire

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

The International Fire Engineering Guidelines[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, it is considered that less severe conditions are more appropriate and tenability should be considered in terms of effective evacuation. Hence in the context of this practice note, it is considered tenability limits as exposure thresholds that cause incapacitation, serious injuries or ineffective evacuation movement.

Purser[8] 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.

3.1.1 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[9, 10, 11] 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).

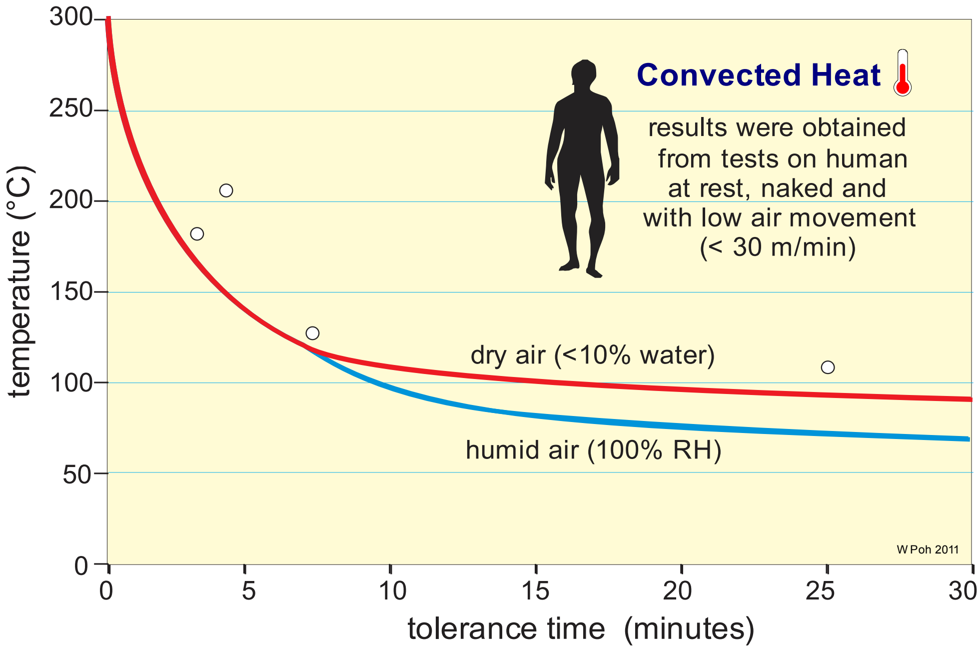

Figure 2: Tolerance to Convected Heat (SFPE[8])

Human tolerance to dry heat is largely attributed to human's ability of evaporative cooling through sweating[12]. 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 by Blockley[13] for estimating tolerance time to convected heat in water saturated environments. This relationship is shown in Figure 2 as the blue line. To account for mid-humidity conditions, an empirical relationship, which lies approximately between the dry and humid lines, is also proposed in Purser[8]. Humidity might be quite high in a sprinkler controlled fire, and although compartment temperatures are not likely to be as high as in the uncontrolled fire scenario, temperatures still may exceed the limits of human tenability.

3.1.2 Radiant Heat

Even without direct contact with flames or 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[9, 10, 14, 15] were conducted to determine the tolerance time for radiant heat exposure to levels ranging from 2.4 kW/m^2 to 23.5 kW/m^2. 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.

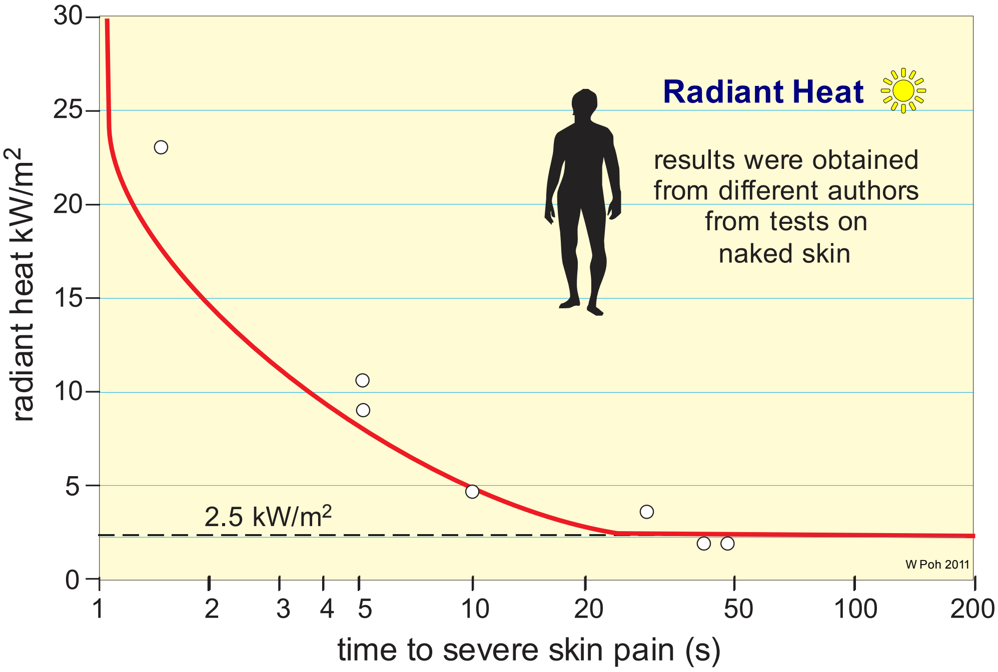

Figure 3: Tolerance to Radiant Heat (SFPE[8])

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 were conducted by Raj[16] where, with the protection of light clothing, the author exposed himself to radiant heat flux of 5.0 kW/m^2 for 30 s without suffering skin pain or burns.

3.1.3 Toxic Gases

In building fires, the most common asphyxiant 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[8, 14] conducted on primates (juvenile baboons and cynomolgus monkeys) by subjecting them to various concentrations of CO and HCN. The results are shown in Figure 4.

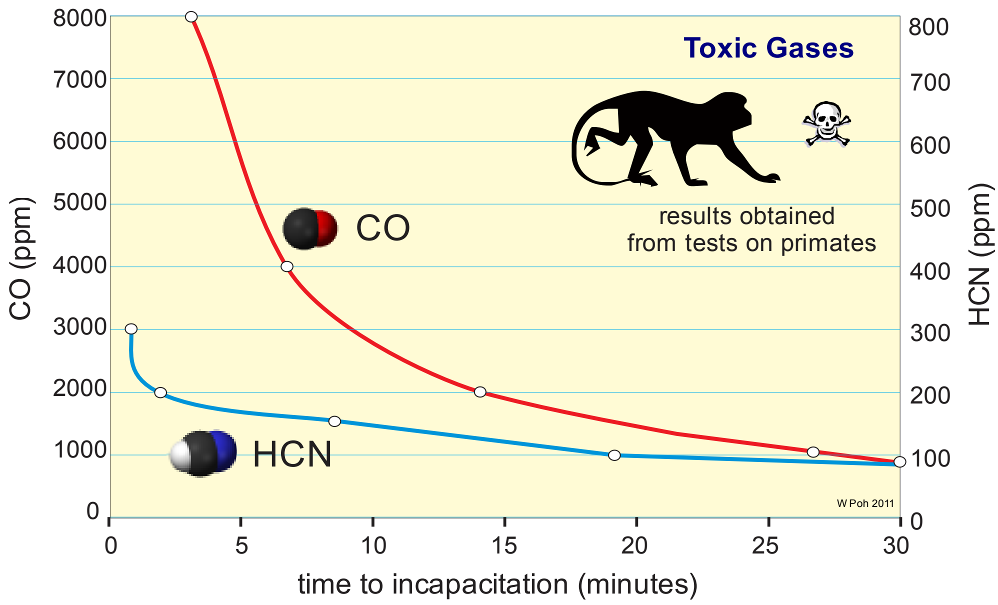

Figure 4: Tolerance to CO and HCN (SFPE[8])

It is assumed that these exposure limits would have a similar effect and impact on humans.

Many other irritants and toxic species are produced in fires in varying quantities depending on the fuel, environmental conditions and other characteristics of the combustion, however the toxicity is generally dominated by the asphyxiant gases (CO and HCN)[8].

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[17, 18]. Note also that low oxygen or high carbon dioxide concentrations also impact breathing rates which increase the uptake of toxic gases. These factors are considered in the calculation of Fractional effective dose (see Section 5.3 below).

3.1.4 Smoke Obscuration

Soot contained in smoke 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[19]. Since this practice note considers the environmental conditions necessary to provide unimpeded egress, the tenability limits states herein generally do not consider reduced walking speeds.

Combustion gases in the smoke may also cause irritation to the eyes. These include acid gases (HF, HCl, HBr, SO_2, NO_x) and organic irritant gases (acrolein, formaldehyde, crotonaldehyde). Their effects have a similar effect to reduced visibility[8] (see Figure 5).

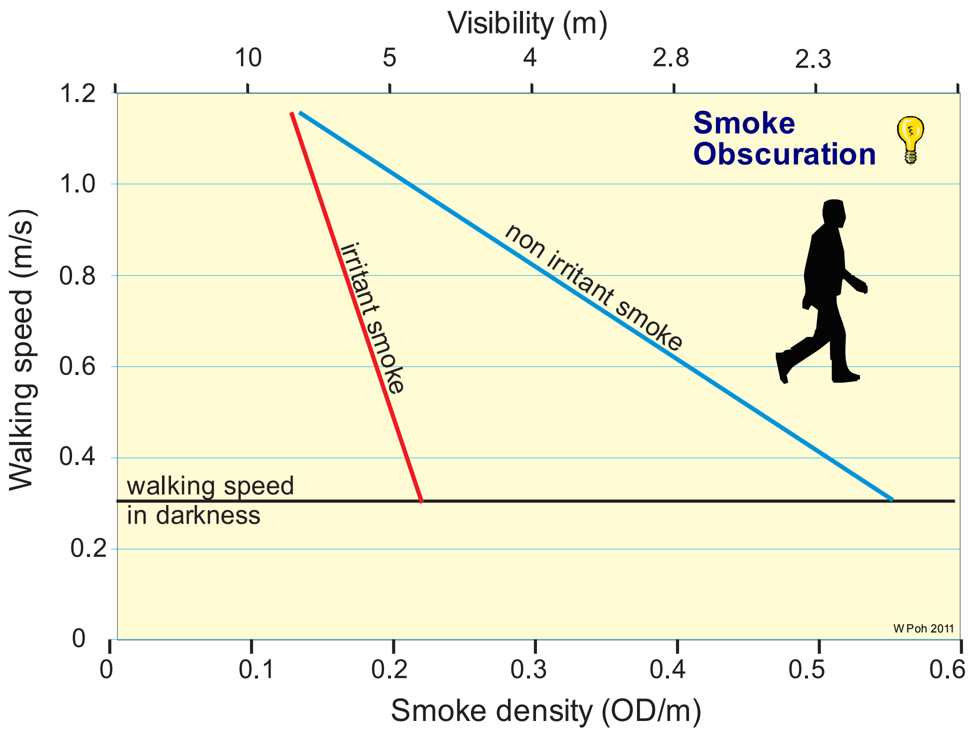

Figure 5: Walking speed versus Visibility (SFPE[8])

If the occupants are located at a substantial 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.

4 Design Approaches

Generally, there are two main approaches to evaluation safety of occupants in building fires. These are discussed below. It is up to the Fire Engineer to make judgement regarding which approach to adopt or indeed if a combination of the approaches is suitable. In making this engineering judgement, it is important to consider the function or use of the building, the likely occupants' characteristics and behaviour, the likely fire hazards and any active fire safety systems installed in the building.

4.1 No Smoke Exposure

The first approach is to ensure that the occupants are not directly exposed to smoke — by keeping the smoke layer above the head height of the occupants (see Figure 6). This height may be assumed to be a minimum 2.0 m above the floor level[1].

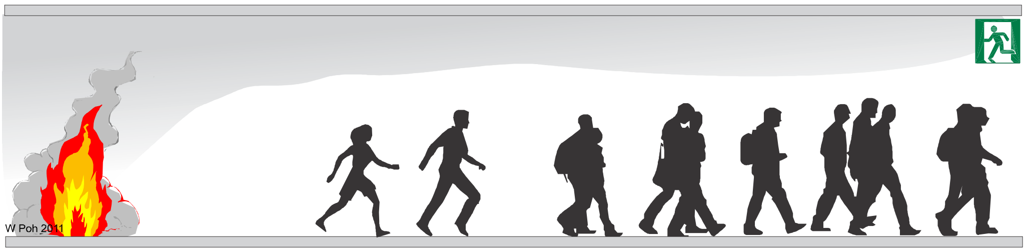

Figure 6: Occupants not exposed to smoke

4.2 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).

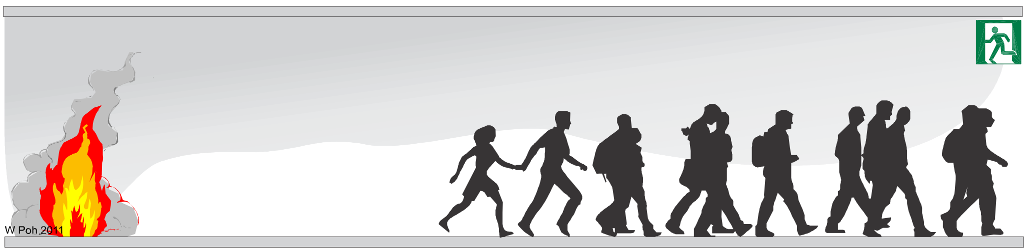

Figure 7: Occupants exposed to smoke

[1] 2.0 m is chosen based on Clause 2(a)(i) of BCA Specification E2.2b and the New Zealand Verification Method[5]

5 Tenability Criteria

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 practice note to suit the design and evaluation approach. These are discussed below in order of increasing rigour of analyses.

Factors of safety are not proposed within this practice note as these are expected to be developed and agreed upon on a project specific basis. Generally the tenability limits proposed herein are considered suitable for determining ASET for most occupant scenarios it is expected that variations in occupant characteristics would be accounted for in the factors of safety applied in the calculation of RSET.

When considering Fractional Effective Dose (FED) it is acknowledged that the distribution of human responses to fire gases is not known. By definition, an FED threshold of 1.0 represents the median value of a distribution, with one-half of the population being more susceptible to an insult (suffering incapacitation at an FED<1) and one-half being less susceptible (suffering incapacitation at an FED>1), however the extent of the distribution is unknown[18]. On this basis, an FED threshold of 1.0 is considered suitable for the vast majority of occupant scenarios, however as always Engineering Judgement should be exercised and lower FED threshold may be appropriate in certain cases such as buildings containing at risk occupant groups whose health would not be expected to be equivalent to the average within the wider population.

5.1 No Exposure

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

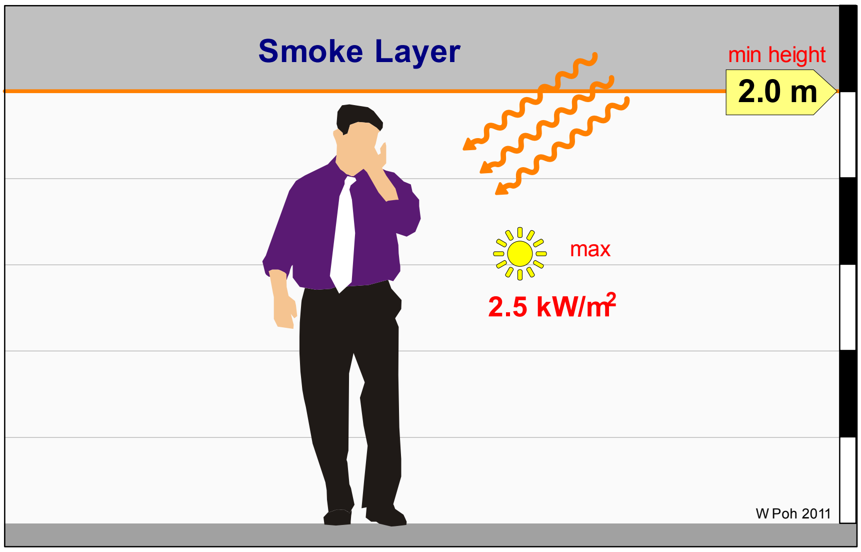

Figure 8 Tenability Criteria - No Exposure

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 received at 2.0 m above the floor level from the fire and the hot smoke layer above does not exceed the severe skin pain threshold of 2.5 KW/m² (based on the asymptote of the fitted curve in Figure 3).

Since the smoke is located above the head height of the occupants, visibility, convected heat and toxic gases of the smoke generally need not be considered (see below). In the majority of cases when the smoke layer is maintained above 2.0 m from the floor level, the lower layer air temperature is not expected to exceed the limits of human tenability. In special cases (e.g. high ambient temperature) this assumption may need to be justified or demonstrated. However, it is noted that the radiant heat threshold of 2.5 kW/m^2 generally may be reached when the hot layer temperature rises above 180-200°C.

Note that in reality hot layer stratification is not perfectly horizontal and where the calculated hot smoke layer height is just above 2.0 m, the limits of visibility, convected heat and toxicity may be exceeded at 2.0 m above the floor. In addition, many zone models and field models include factors to account for vent sheer flow entrainment, a phenomenon whereby cool air entering a room entrains some of the upper layer gases into the lower layer. As a result, it is possible for such models to produce results where the hot smoke layer height remains above 2.0 m, but the tenability limits for visibility, convected heat or toxicity are exceeded in the lower layer. Based on these factors, it is recommended that either the full suite of tenability criteria be verified as per the approach outlined in Section 5.2 or an appropriate margin of safety be applied to the hot smoke layer height calculation.

5.2 Short Exposure

For simple 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 8 may be used.

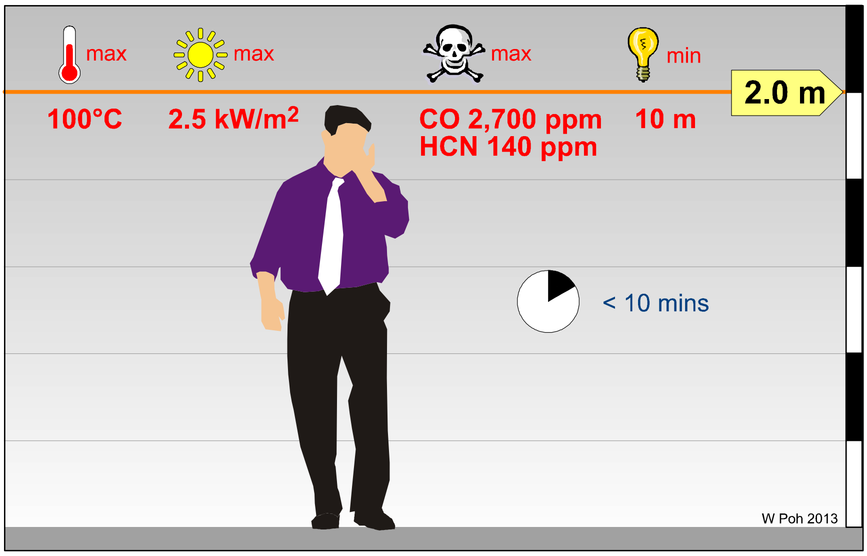

Figure 8: Tenability Criteria – Short Exposure

Conditions are considered to be untenable when any of the above criteria in Figure 8 are exceeded.

The criteria for convected heat and toxic gas exposures are obtained from tolerance limits in Figure 2, Figure 3 and Figure 4, assuming a maximum 10-minute exposure. The air environment is conservatively assumed to be humid in establishing the tolerance to convective heat. The smoke hazards are evaluated at a height of 2.0 m above the floor.

The visibility limit of 10 m is suitable for large enclosures to assist occupant way finding. For small enclosures (dimensions in the order of 10 m), a lower visibility limit of 5 m may be used[8]. A reduced visibility (< 10 m) distance may be acceptable in isolated areas for areas where occupants may be queuing adjacent to exits, subject to assessment of CO and HCN levels.

Although it is acknowledged that incapacitation due to toxic gases is dependent on exposure time, the dose [ppm.min] required for incapacitation due to CO exposure is relatively constant (regardless of the concentration [ppm]) being approxiamtely 27,000 ppm.min[8]. Therefore in a hypothetical fire scenario where the CO concentration was just below 2,700 ppm for a period of 10 minutes, incapacitation would not be expected as the total dose would not exceed 27,000 ppm.min. However if the concentration of CO spiked above 2,700 ppm the tenability criteria would be considered to have been reached[2].

In the case of HCN, higher concentrations result in more rapid incapacitation, however the most conservative value[8] has been chosen for the tenability limit.

Similarly, 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 the short exposure criteria. Such exposure is less severe than the constant

[2] In such scenarios it may be appropriate to use the more detailed 'General Exposure' Tenability criteria described in Section 5.3.

exposure to 100°C over the entire period. From this viewpoint, this, and similarly the criteria for toxic gas exposure, are generally quite conservative. Although the concentration of other irritant and toxic gases is not considered in this simple criteria, nor are the effects of increased uptake of asphyxiants due to potential increased breathing rates, these effects are not considered to be significant enough that the short exposure model for tenability criteria is invalid.

5.3 Extended Period Exposure

For situations where the occupants may be exposed to smoke for longer durations of up to 30 minutes, a more general and rigorous analysis using Fractional Effective Dose (FED) method (as outlined in the SFPE handbook and ISO 13571[8, 18]) 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. In instances where an additional level of conservatism is desired, an FED less than 1 may be a more suitable threshold for 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 O_2 and CO_2 may also be included in the calculation[8]. Using this method, the tenability criteria are shown in Figure 9.

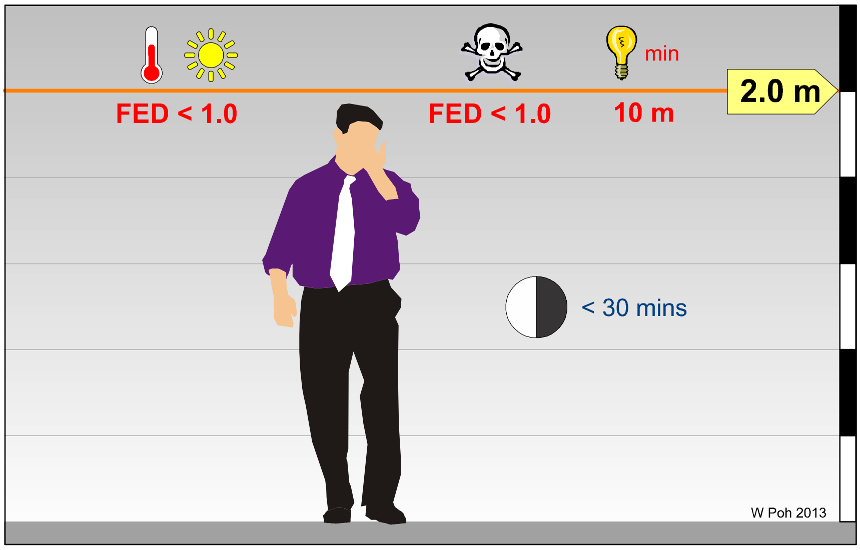

Figure 9: Tenability Criteria – General Exposure

Again, for the sake of convenience, the FEDs are evaluated at the height of 2.0 m.

The visibility limit of 10 m is also adopted here, again being suitable for large enclosures to assist occupant way finding. For small enclosures (dimensions in the order of 10 m), a lower visibility limit of 5 m may be used.

Alternatively a similar approach to FED may also be used to determine the fractional effective concentration (FEC) of combustion gases that cause irritation to the eyes and respiratory tracts[8, 18], including acid gases (HF, HCl, HBr, SO_2, NO_x) and organic irritant gases (acrolein, formaldehyde, crotonaldehyde). The FEC may be used to modify the walking speed of the occupants, however for the purposes of this practice note FEC = 1.0 represents incapacitation or cessation of effective evacuation movement.

5.4 Fire Brigade Operations

Determining the appropriate tenability criteria to use for fire-fighters in various applications is an issue that frequently arises during fire engineering brief discussions and requires further guidance. In addition, the ABCB have a priority to quantify the Performance Requirements of the BCA. One approach adopted by other jurisdictions, such as New Zealand, has been the development of a Fire Safety Verification Method. Such an approach is likely to require the determination of the time for fire brigade intervention, which further demonstrates the need for guidance in the area of fire fighter tenability criteria.

Whilst AFAC are working on preparing further guidance in this area, it is recognised that at this point in time the approach to determining the appropriate criteria to use should still be based on consultation with the relevant fire authority, taking into consideration site specific hazards and probable intervention requirements.

The critical factors of the internal building environment in the event of a fire which affect firefighters and their equipment are:

- Air temperature;
- Visibility;
- Humidity;
- Incident thermal radiation;
- Air flow past the firefighter; and
- Exposure time.

For the purpose of assessing the safety of the fire brigade personnel, the criteria set out by Australasian Fire Authorities Council (AFAC)[21] may be used. These are summarised in Table 1.

Table 1: Exposure limits for fire fighters under various condition

	Routine Condition	Hazardous Condition	Extreme Condition	Critical Condition
Maximum Time	25 minutes	10 minutes	1 minute	< 1 minute
Maximum Air Temperature	100°C	120°C	160°C	> 235°C
Maximum Radiation	1kW/m^2	3kW/m^2	4 - 4.5kW/m^2	> 10kW/m^2

Figure 10 shows the AFAC criteria for fire fighters for exposure of up to 10 minutes.

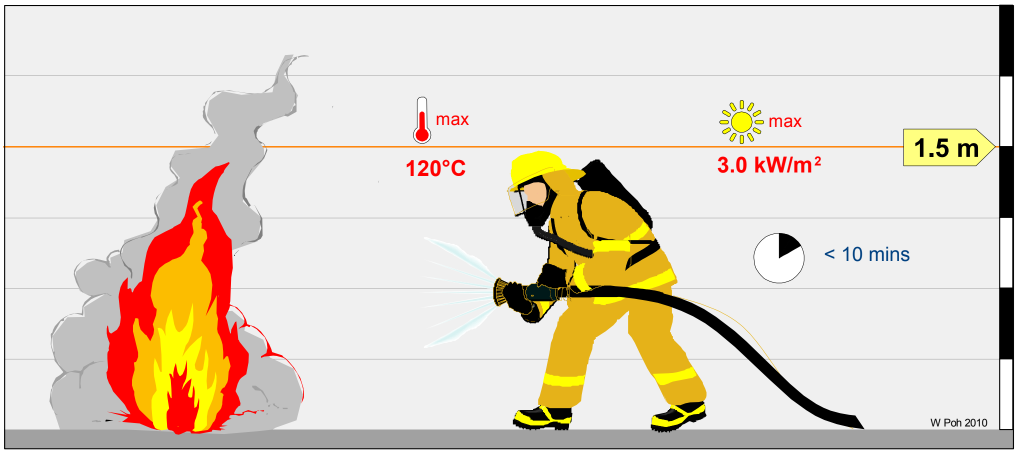

Figure 10: Tenability for Fire Fighters (up to 10 minutes)

The limits in Table 1 were developed based on comfort levels reported during some tests conducted in 1994[22]. These results are based on fire fighters dressed in standard A26 tunics with over-trousers to an equivalent specification, firehoods, gloves helmets, rubber boots and breathing apparatus. All conditions are relative to height of 1.5m above floor level.

The radiant heat limit of 1.0 kW/m^2 for routine fire fighting condition was nominally set. Review of more recent test results[16] indicates that a higher limit may be more appropriate, since it is lower than the heat flux received from sun bathing in the tropics, which is estimated to be 1.1 kW/m^2 [23].

The appropriate limit used should be determined in consultation with the relevant fire authority, taking into consideration site specific hazards and probable intervention requirements.

The final factor of visibility should also be determined in consultation with the relevant fire authority, taking into consideration site specific hazards and probable intervention requirements. This would include the need to find the seat of the fire, undertake fire-fighting activities and undertake search and rescue.

It is noted that at the time of publishing this practice note, an AFAC Guideline for fire-fighter tenability was in development. This guideline proposes to include consideration of scenarios where visibility may also need to be considered for fire brigade intervention.

6 Conclusion

This practice note provides guidance to assist building designers in better understanding tenability criteria in building fires. The background for the basis of tenability is presented and three approaches are presented with relevant tenability criteria that are recommended for adoption. Tenability criteria for fire brigade operations have also been briefly discussed.

7 Disclaimer

The information contained in this Practice Note: is to be used only as a guide and is not intended to be universal or prescriptive; is intended to assist FSEs in determining how to comply with statutory requirements; is subject to change without notice; and to the extent permitted by law, is provided without warranties of any kind, either express or implied.

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