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Application of fire safety engineering principles to the design of buildings

Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6)

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Summary of pages

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Foreword

Publishing Information

This Published Document is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 March 2019. It was prepared by Technical Committee FSH/24, *Fire safety engineering*. A list of organizations represented on this committee can be obtained on request to the committee manager.

Supersession

This Published Document supersedes PD 7974-6:2004, which is withdrawn.

Relationship with other publications

The parts of PD 7974 are structured as follows:

- PD 7974-1, *Initiation and development of fire within the enclosure of origin*;
- PD 7974-2, *Spread of smoke and toxic gases within and beyond the enclosure of origin*;
- PD 7974-3, *Structural response and fire spread beyond the enclosure of origin*;
- PD 7974-4, *Detection of fire and activation of fire protection systems*;
- PD 7974-5, *Fire service intervention*;
- PD 7974-6, *Occupant evacuation, behaviour and condition*; and
- PD 7974-7, *Probabilistic fire risk assessment*.

This series of Published Documents are intended to be used in support of [BS 7974](#), but do not represent the only means of satisfying the recommendations of the code of practice.

Information about this document

Text introduced or altered by Corrigendum No. 1 is indicated in the text by tags C1 C1. Minor editorial corrections are not tagged.

This Published Document can be used to set specific acceptance criteria and undertake detailed analysis for escape and tenability. It can be used to identify and define one or more fire safety design issues to be addressed using fire safety engineering.

This is a full revision of the Published Document, and introduces the following principal changes.

- The principal guidance and bibliography have been updated in line with recent developments and publications since 2004.
- The data tables in the annexes have been expanded to include more recently published data and bibliography.
- A full set of expressions has been provided for fractional effective dose calculations with worked examples to illustrate the calculation methods.

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Use of this document

This publication is not to be regarded as a British Standard.

As a guide, this Published Document takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice.

It has been assumed in the preparation of this Published Document that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

Presentational conventions

The guidance in this document is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is “should”.

Additional commentary, explanation and general informative material is presented in smaller italic type.

Where words have alternative spellings, the preferred spelling of the *Shorter Oxford English Dictionary* is used (e.g. “organization” rather than “organisation”).

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In particular, attention is drawn to Approved Document B of the Building Regulations 2010 [\[1\]](#).

Introduction

This Published Document provides information regarding engineering methods currently available for the evaluation and management of occupant behaviour, particularly escape behaviour, during a fire emergency and for the evaluation of occupant condition, especially in relation to exposure to fire effluent and heat.

Most cases of fire involve evacuation of the occupants. A basic principle of a performance-based (fire safety engineering) building design is that the available safe escape time (ASET) is greater than the required safe escape time (RSET) by an appropriate margin of safety. An appropriate margin of safety takes account of the risks associated with different potential fire scenarios and the uncertainties in the prediction of ASET and RSET for particular design scenarios (see Purser, 2003 [2]). Uncertainties for specific ASET and RSET parameters are considered in this Published Document. Assessment of overall safety margin for a design is considered in [BS 7974](#).

An ideal fire safety design ensures that building occupants are able to reach a place of relative or ultimate safety without ever coming into contact with or even being aware of fire effluent and/or heat. This is the main design criterion for the safety of the majority of occupants in multi-compartment buildings (see [BS 7974](#) and [BS ISO/TR 13387-8](#)). A major design criterion is therefore the estimation of the time required for escape in situations where occupants are not directly affected by fire effluent or heat.

There will inevitably be some potential scenarios when some occupants become aware of or are exposed to fire effluent, particularly when the occupants are in the enclosure of fire origin. This can vary between seeing fire or smoke or exposure to slight smoke contamination, common in many accidental fires, to life threatening exposures such as in major fire disasters. For all of these types of scenarios, it is important to be able to assess the likely effects of such exposures, either as part of the main design or as part of a risk assessment.

To achieve these evaluations, detailed input information is required in four main areas:

- a) the building design and emergency life safety management strategy;
- b) the occupant characteristics including human behaviour;
- c) the fire simulation dynamics; and
- d) intervention effects.

The response of occupants to a fire condition is influenced by a range of variables in these four categories, related to the characterization of the occupants in terms of their number, distribution within the building at different times, their familiarity with the building, their abilities, behaviours and other attributes; the characterization of the building including its use, layout and services; the provision for warnings, means of escape and emergency management strategy; the interaction of all these features with the developing fire scenario; and provisions for emergency intervention (by fire and rescue services).

Guidance is provided on the evaluation of escape and evacuation times from buildings:

- in the absence of fire and where occupants are not directly affected by a fire – for example in building locations remote from the fire compartment;
- when the escape behaviour of occupants and therefore RSET is influenced by fire, specifically by fire effluents and heat; and
- the evaluation of ASET in relation to tenability limits due to fire effluents and heat.

The time required for escape depends upon a series of processes consisting of:

- 1) time from ignition of fuel resulting in a fire to detection;
- 2) time from detection of a fire to the provision of a general evacuation warning to occupants; and
- 3) evacuation time, which has two major components:
 - pre-travel time – this consists of the time required after a warning to recognize the emergency and then respond by carrying out a range of activities before travelling to exits; and
 - travel time (the time required for occupants to travel to a place of safety).

NOTE 1 See Purser, 2003 [3] for further information.

For detection, warning and pre-travel recognition and response times, research regarding human behaviour in the event of fire has been essentially qualitative, describing the psychological, behavioural and physiological factors affecting detection and recognition of fires and the wide range of pre-travel behaviours engaged in by groups of occupants. Some studies have included measurements of the times for which these behaviours were engaged in, which can be used as input to evacuation time calculations.

NOTE 2 For further information, see BS ISO/TR 13387-8; Purser, 2003 [2]; Canter, 1990 [4]; Sime, 1988 [5]; Sime, 1998 [6]; Purser and Bensilum, 2001 [7]; Proulx and Fahy, 1997 [8]; Bryan, 2002 [9]; and Bryan, 1977 [10].

The results of this work have provided an understanding of the complexities of human behaviour during fire emergencies and escape from occupied buildings and the profound effects of the behavioural activities engaged in before the travel phase of evacuation on escape and evacuation times. In many situations, these pre-travel processes and activities comprise the greatest part of the time required for escape, while for evacuation engineering calculations most attention has historically been directed to the travel phase.

NOTE 3 See Purser, 2003 [2]; Purser, 2003 [3]; Canter, 1990 [4]; Sime, 1988 [5]; Sime, 1998 [6]; Purser and Bensilum, 2001 [7]; Proulx and Fahy, 1997 [8]; Bryan, 2002 [9]; and Bryan, 1977 [10].

Previous methodologies have attempted to provide qualitative evaluation based upon different occupancy criteria to inform designers regarding aspects that are likely to affect evacuation timing and efficiency; however, since they were not linked with quantitative performance data they could not be used to develop engineering analytical calculations to evaluate escape time (see Sime, 1998 [6]). Current methods presented in this Published Document make use of published quantitative data on escape and evacuation parameters for application to escape and evacuation time calculations.

In an earlier draft version of the design guidance (DD 240-1), attempts were made to relate pre-travel time solely to the type of warning system used (sounder, recorded voice message or direct personal address message). Although the type of warning system has been found to be one important parameter, subsequent research has shown that in many situations additional features, especially the fire safety management system and occupant characteristics, are more important aspects influencing escape parameters, especially warning and pre-travel times. Guidance on these aspects was included in the 2004 edition of this Published Document, but the available data were limited at that time. Work in this area has expanded considerably in recent years, which is reflected in the updated guidance in this edition.

References to specific sources of information are cited throughout this Published Document. Two sources of information and guidance for evaluating aspects of occupant escape behaviour and condition (effects of exposure to heat, smoke and toxic gases) from the Society of Fire Protection Engineers (SFPE) are particularly recommended. The behaviour and condition chapters in the *SFPE Handbook of Fire Protection Engineering* [11] have been considerably expanded in the 5th

Edition, with references to specific chapters included in this Published Document. In addition, the SFPE has also published a second edition of the *Guide to Human Behaviour in Fire* [12] which contains useful information on the evaluation of behaviour and condition.

NOTE 4 For further information, see BS ISO/TR 13387-8; Purser, 2003 [2]; Canter, 1990 [4]; Sime, 1988 [5]; Sime, 1998 [6]; and Purser and Bensilum, 2001 [7].

At the time of publication the only method available for the quantification of these behavioural phenomena is by observation, measurement or analysis of actual incidents or simulated emergency experiments. For these data to be of value for application to RSET calculations they are assigned to specified behavioural scenarios, designated in terms of features influencing behaviour, including occupancy type, occupant characteristics, fire safety management strategy and warning system (see Nilsson and Fahy, 2016 [13]). A number of data sets are now available for a range of occupancy types, which are summarized in [Clause 6](#). These have been used to develop guidance for pre-travel times for different design behavioural scenarios.

NOTE 5 See Purser and Bensilum, 2001 [7]; Proulx and Fahy, 1997 [8]; Proulx and Sime [14]; and Gwynne and Boyce, 2016 [15].

Travel to and through exits and escape routes involves physically-based processes more amenable to relatively simple calculation methods for design purposes (see references [2], [16], [17], [18], [19], [20], [21]). However, travel times can be affected by behaviours such as wayfinding and exit choice (see references [2], [4], [6] and [7]) and certain physical phenomena such as merging flow, for which calculation parameters have not been fully solved (see references [3], [22], [23] and [24]).

There is considerable interaction between the various aspects of pre-travel and travel times in the determination of total evacuation times for groups of building occupants. This has important implications for design performance evaluations (see references [2], [7], [16] and [22]). A range of human behaviours can be involved to a greater or lesser extent in all these phases of escape time.

The guidance in this Published Document on evaluation of occupant behaviour and condition is intended to be considered with the guidance from the other documents in the 7974 series as part of an overall performance-based design as set out in [BS 7974](#).

1 Scope

This Published Document is intended to provide guidance to designers, regulators and fire safety professionals on the engineering methods available for the evaluation of life safety aspects of a fire safety engineering design in relation to escape and tenability strategies.

The objective of the fire safety engineering strategy is to ensure exposure to the effects of fire does not impede the safe escape of occupants or cause exposure to conditions leading to adverse health effects.

Guidance is presented regarding the evaluation and management of occupant behaviour during a fire emergency and for the evaluation of occupant condition related to exposure to fire effluent and heat.

This Published Document addresses the parameters that underlie the basic principles of designing for life safety and provides guidance on the processes, assessments and calculations necessary to determine the location and condition of the occupants of the building, with respect to time. This is achieved using the information presented on the evaluation, quantification and management of occupant behaviour, particularly escape behaviour, during a fire emergency.

This Published Document also provides a framework for reviewing the suitability of an engineering method for assessing the life safety potential of a building for its occupants.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes provisions of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

[BS 7974](#), *Application of fire safety engineering principles to the design of buildings – Code of practice*

3 Terms, definitions, symbols and abbreviations

3.1 Terms and definitions

For the purposes of this Published Document, the terms and definitions given in [BS ISO/TR 13387-8](#) and the following apply.

3.1.1 alarm time

interval between detection of a fire and the time at which a general warning is provided to all occupants in a specified space within a building

NOTE A warning consists of an audible alarm signal from a sounder, by human voice directly or using a public address/voice alarm (PA/VA) system either live or by a recorded message to indicate an emergency either requiring immediate evacuation or a need to be prepared for further instructions.

3.1.2 available safe escape time (ASET)

calculated time available between the time of ignition and the estimated time at which conditions become untenable

3.1.3 cue (to a fire)

indication to occupants that a fire exists

NOTE Fire cues include odours, fire noises, sight of smoke or flames, voice warnings and alarm sounders, or illuminated warning displays.

3.1.4 design behavioural scenario

qualitative description of occupant characteristics, the built environment and systems, and fire dynamics, identifying key aspects affecting escape behaviours and escape time for which numerical data can be gathered

3.1.5 detection time

interval between the onset of combustion and its detection by an automatic system or otherwise

NOTE Where a decision that a fire has been detected involves a human response, detection is the end result of a process whereby different cues to the existence and severity of a fire are considered to require an evacuation alarm or warning to be issued.

3.1.6 enclosure

space within a building defined by boundary elements (on all sides)

NOTE 1 In the context of this Published Document, this signifies enclosures that might contain occupants, such as a room, corridor or stair.

NOTE 2 An enclosure may or may not constitute a fire compartment.

3.1.7 escape route

route forming means of escape from any point in a building to enable the safe movement of persons to a place of relative or ultimate safety

3.1.8 escape time

interval between ignition and the time at which all occupants are able to reach place of safety

3.1.9 evacuation time

interval between the time at which a warning of a fire is transmitted to the occupants and the time at which all of the occupants are able to reach a place of safety

3.1.10 exit

doorway or other suitable opening giving access towards a place of safety

3.1.11 fire compartment

building or part of a building constructed to prevent the spread of fire or fire effluent to or from another part of the same building or an adjoining building

3.1.12 fire scenario

set of circumstances, chosen as an example, that defines the development of fire and the spread of combustion products throughout a building or part of a building

3.1.13 flow time

time required for a group of occupants to pass through a specific exit or set of exits from an enclosure or building

3.1.14 impaired person

person having a specified health condition

NOTE This includes exteroceptive senses, interoceptive senses or a person who cannot walk 200 m without a rest or walking aid (such as the elderly, persons with injuries, pregnant women, wheelchair users).

3.1.15 management

task(s) carried out by a defined individual or individuals empowered and resourced to ensure moral, legal and financial obligations are met in respect to the management of fire safety

NOTE In the context of this Published Document, management refers in particular to those aspects affecting the time required to initiate and manage a timely and efficient occupant evacuation.

3.1.16 margin of safety

quantity or time factor applied to a design calculation or performance requirement to allow for uncertainties and/or statistical distributions of parameters relevant to the design performance

NOTE In relation to occupant behaviour and evacuation, an adequate margin of safety takes account of the risks associated with different types of occupancies and the people likely to use those occupancies, as well as potential fire scenarios and the uncertainties in the prediction of ASET and RSET for particular design scenarios.

3.1.17 means of escape

means whereby a safe, defined route or routes in the event of fire is or are provided for persons to travel from any point in a building to a place of relative and/or ultimate safety

3.1.18 merge ratio

proportional share of downstream flow accounted for by flows that have met at merge points

3.1.19 model

information, mathematical modelling, data, assumptions, boundary conditions and mathematical equations that describes the (physical) system or process of interest

3.1.20 phased evacuation

process by which people immediately at risk are evacuated before others

NOTE Typically a process by which a limited number of floors (usually the fire floor and the storey above) is evacuated initially and the remaining floors are evacuated when necessary.

3.1.21 place of safety

predetermined place in which persons are in no immediate danger from the effects of fire

NOTE 1 The place of safety may be inside or outside the building, depending upon the evacuation strategy.

NOTE 2 A relative place of safety or safe refuge can be represented by a protected escape route or other form of protected compartment. A place of ultimate safety would be outside the building at a safe distance from it.

3.1.22 presentation time

interval between the time at which a warning of a fire is given and the time at which a person reaches an exit

3.1.23 pre-travel time

interval between the time at which a warning of a fire is given and the time at which movement towards an exit begins

NOTE 1 Pre-travel time consists of two components: recognition time and response time.

NOTE 2 For groups of occupants, two phases can be recognized: the pre-travel time of the first occupants to move; and the pre-travel time distribution between the first and last occupants to move.

NOTE 3 Although occupants might engage in activities involving movement during the pre-travel time, these do not include movement towards an exit.

3.1.24 progressive evacuation

process by which people immediately at risk are moved through a series of one or more safe (flame and smoke) resistant compartments either vertically or horizontally within a building while monitoring the developing situation before deciding to move others

NOTE Where occupants are evacuated from fire threatened areas to protected spaces within a building, especially for tall buildings, a dynamic risk assessment is required. If fire or effluent continues to spread then a total evacuation might become necessary before escape routes become compromised.

3.1.25 recognition time

interval between the time at which an alarm warning of a fire is given and the first observable response to the warning

NOTE Depending on the scenario, occupants might be aware of various fire cues (for example odour, seeing smoke or flames) before or after a warning is given, which could influence their recognition time and behaviour.

3.1.26 required safe escape time (RSET)

calculated time available between ignition of a fire and the time at which occupants in a specified space in a building are able to reach a place of safety

3.1.27 response time

interval between the time at which the first observable response to the event occurs and the time at which movement begins towards an exit

3.1.28 safe refuge

temporary location which is free from immediate danger from the effects of fire

NOTE A safe refuge is, for example, a place where a wheelchair user can wait in relative safety for further assistance. It can also be a waiting area in high-rise buildings which gives people a chance to rest before continuing their escape to a place of safety.

3.1.29 simultaneous evacuation

immediate evacuation of all occupants on sounding of an alarm

3.1.30 stay put strategy

strategy involving evacuation of people immediately at risk

NOTE 1 Other occupants may remain within a fire (flame and smoke) resisting compartment. Evacuation of other occupants might not normally be necessary. Especially for tall buildings, a dynamic risk assessment is required. If fire or effluent spreads beyond the compartment of fire origin, then a total evacuation might become necessary before escape routes become compromised.

NOTE 2 This is also known as a defend in place strategy.

3.1.31 tenability

ability of humans to perform cognitive and motor-skill functions and behaviours at an acceptable level when exposed to a fire environment so as to be able to take effective action to escape to a safe refuge or place of ultimate safety

NOTE If exposed individuals are able to perform cognitive and motor-skill functions at an acceptable level, the exposure is said to be tenable. If not, the exposure is said to result in compromised tenability.

3.1.32 tenability criteria

maximum exposure to hazards from a fire that can be tolerated without violating safety goals

3.1.33 travel distance

actual distance to be travelled by a person from any point within a building to the nearest exit, having regard to the layout of walls, partitions, furnishings and fittings

3.1.34 travel time

time needed, once movement towards an exit has begun, for all occupants of a specified part of a building to reach a place of safety

NOTE Important aspects are travel time for occupants to evacuate the enclosure of origin and enter a protected escape route, and travel time for occupants to enter and pass through escape routes to reach a place of safety.

3.1.35 unrestricted walking speed

unrestricted speed of movement of a person

NOTE This represents the walking speed any individual unrestricted by proximity to others.

3.1.36 walking time

time taken for a person to walk from their starting position to the nearest exit

3.2 Symbols and abbreviations

A_s	=	total standing area (m ²) on stair
ATPS	=	atmospheric pressure and temperature saturated
α_k	=	light extinction coefficient (m ⁻¹)
D	=	optical density per unit path length of the smoke (m ⁻¹)
F_s	=	specific flow (persons.m ⁻¹ .s ⁻¹)
FEC	=	fractional effective concentration
FED	=	fractional effective dose
F_{IN}	=	fraction of an incapacitating dose of all asphyxiant gases
F_{ICO}	=	fraction of an incapacitating dose of CO (Carbon Monoxide)
F_{ICN}	=	fraction of an incapacitating dose of HCN (Hydrogen Cyanide)
t_{ASET}	=	available safe escape time (min)
t_{RSET}	=	required safe escape time (min)
Δt_{esc}	=	escape time (min)
Δt_{det}	=	time to detection (min)
Δt_{evac}	=	time for evacuation (min)
Δt_{warn}	=	time to a general alarm or warning (min)
Δt_{pre}	=	pre-travel time (min)
Δt_{pres}	=	presentation time (min)
Δt_{trav}	=	travel time (min)
$\Delta t_{trav(walking)}$	=	walking time during travel time (min)
$\Delta t_{trav(flow)}$	=	time required to flow through the exits (min)
Δt_{rec}	=	recognition time (min)
Δt_{res}	=	response time (min)
Δt_{queue}	=	time to queue (min) formation
r	=	radiant heat exposure dose [(kW.m ⁻²) ^{4/3} .min] required for any given endpoint
q	=	radiant heat flux (kW.m ⁻²)
S	=	walking speed (m.s ⁻¹)
t	=	exposure time (min)
t_{margin}	=	adequate margin of safety (min)
T_p	=	time of passage (min)
V_E	=	ventilation (L/min ATPS) depending on activity and body size of subject
V_{CO2}	=	multiplication factor for CO ₂ -induced hyper-ventilation

W_{eff} = effective width (m)

W_s = stair width (m)

4 Principles

4.1 How behaviour, movement and condition are integrated into performance-based design

The main aim of a performance-based design is to provide a safe environment for building occupants for as long as they need to remain in the building and to provide for safe means of escape with sufficient capacity for all occupants to be able to evacuate in safety. The framework for an engineering approach to the development of a performance-based design for means of escape is described in [BS 7974](#), for which the methods in this Published Document provide guidance on human factors.

The traditional basis of prescriptive life safety design is concentrated on physical provisions for means of escape. The advantage of the prescriptive method is that it can usually achieve acceptable levels of safety by the application of what is relatively simple guidance that has been found to work empirically. Whilst this prescriptive guidance is not primarily time-based, the elements related to exit and stair provision are based on time-related evacuation flow calculations.

Prescriptive rules on travel distance, floor space factors and exit requirements interact and control considerably more than just these stated parameters. For this reason the methods described in this Published Document cannot be applied directly to modifications of a prescriptive design. Any such performance-based modification would require a full consideration of performance-based aspects in accordance with [BS 7974](#).

The fire safety engineering approach adopted in [BS 7974](#) considers a performance-based approach to achieve an overall objective of fire safe design. The holistic design – described in more detail in [BS 7974](#) and the other Published Documents – is subdivided into a series of sub-systems. One principle is that inter-relationships and inter-dependencies of the various sub-systems are appreciated, and that the consequence of all the considerations taking place in any one sub-system are identified and realized. For this Published Document, the main consideration is that the time available for safe escape exceeds that required for escape by an acceptable safety margin.

4.2 The basis of performance-based design

The basis of both prescriptive and performance-based life safety design consists of provisions for the protection of occupants from fire exposure and provision for means of escape. This in general includes:

- a) adequate escape route provision (number and width of exits and protected escape routes, travel distances to exits);
- b) estimates and controls on occupant number and density (e.g. floor space factors);
- c) provision of warnings (manual or automatic detection and alarm system, fire safety management);
- d) provision of signage and emergency lighting systems;
- e) provision of refuge facilities with a means of communication to a manned location;
- f) inhibition of internal and external fire spread through control of resistance to flame spread and limitation on rate of heat release and rate of fire growth;
- g) fire separation (passive protection between compartments, passive protection of escape routes, fire and smoke doors and lobbies); and

- h) provision for active fire protection (sprinklers, smoke extraction).

Performance-based fire safety engineering (FSE) design as set out in [BS 7974](#) and this Published Document also considers these basic physical and management provisions to ensure life safety, but the design evaluation is dependent upon a time-based comparison between time available for occupants to escape or to reach a place of relative safety (if necessary) or to a place of ultimate safety. The available safe escape time (ASET) and the escape time, referred to as the required safe escape time (RSET), provides a means of demonstrating that the fire safety design meets the performance criteria established in the qualitative design review (QDR).

Where there are unavoidable design deviations from prescriptive design codes and standards (due to complexities of the building design), a performance-based design can be used, provided an acceptable level of fire safety performance can be achieved.

4.3 ASET calculations

Time available for escape depends upon parameters related to the developing hazard to occupants from the fire. From the moment a fire starts, its sphere of influence increases, threatening larger areas and more occupants. Therefore, for each space, or set of communicating spaces, there is an available safe escape time (ASET) for the occupants to evacuate to a safe location without being exposed to untenable conditions (i.e. conditions under which occupants are unable to take effective action to escape).

Although it is useful to calculate ASET for occupants in particular areas of a building, such as that for occupants of the enclosure of fire origin, the main focus should be on the ASET at the breathing zone of the occupants, which depends on their exposure to fire effluents and heat as they move within different areas of the building and through the escape routes.

Assessment of these processes for any particular scenario is aimed at calculating the time when an occupant would receive an incapacitating exposure to fire effluent and heat.

For some occupancies, a stay put strategy (sometimes known as a defend in place strategy) may be used, whereby occupants in some areas remain in their location while those in other areas evacuate. In such cases the conditions in the stay put areas should remain tenable as long as required.

The prediction of ASET times requires estimation of the time-concentration (or intensity) curves for the major toxic products, smoke and heat in a fire (which is covered by PD 7974-1, PD 7974-2 and PD 7974-3) and on the derivation and estimation of ASET endpoints of occupants for these hazards (which is covered in this Published Document).

4.4 RSET calculations

The RSET calculation considers a number of variable parts to arrive at an overall estimation of escape time. These constituent parts consist of detection time, alarm or warning time, evacuation time to a place of relative safety or ultimate safety, and a margin of safety.

The characterization and determination of evacuation behaviour and evacuation time can be simplified in terms of two broad components.

- a) Pre-travel behaviours (sometimes known as pre-movement or pre-evacuation behaviours): those involved in the responses of occupants before they start to move towards and through escape routes. Although pre-travel behaviours could involve periods when occupants are inactive, they also include a range of behaviours involving movement, but these behaviours do not generally include movement towards the escape routes. An important finding of behavioural research is that the pre-travel phase can often comprise the longest part of the total escape time

(see Purser, 2003 [2]; Purser, 2003 [3]; Sime, 1998 [6]; Purser and Bensilum, 2001 [7]; Proulx and Sime [14]; and Purser, 2001 [25]). Pre-travel time consists of two components:

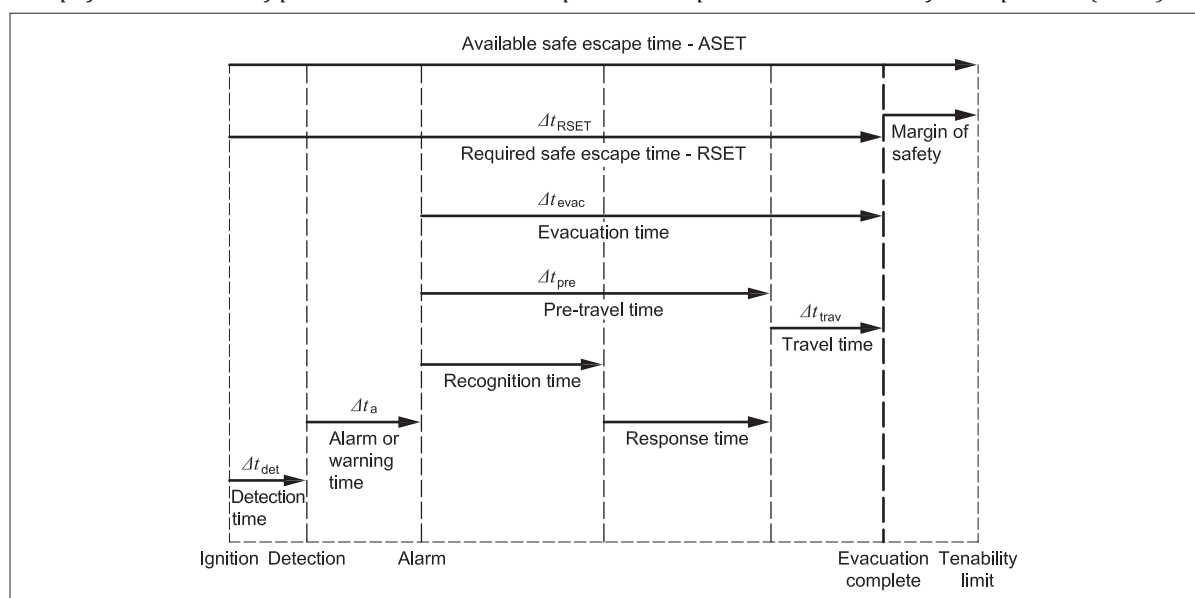
- 1) recognition: the interval between the time at which a warning of a fire is given and the first observable response to the warning; and
 - 2) response: the interval between the time at which the first observable response occurs and the time at which occupants start to move towards an exit.
- b) Travel behaviours: those involved in physical movement of occupants towards, into and through escape routes.

Where occupants are predicted to see fire or smoke during an evacuation, or to be exposed to heat or fire effluent, their pre-travel and travel behaviours might be affected, in which case the fire condition data (see 4.3) should be taken into account. Guidance on the effects of the fire condition on RSET are provided in this Published Document.

A simplified scheme of the processes related to escape is illustrated in Figure 1.

Assessment of these processes for any particular fire scenario is aimed at calculating the RSET.

Figure 1 — Simplified schematic of processes involved in escape time compared to available safe escape time (ASET)



4.5 Effects of fire detection and activation of fire protection systems on ASET and RSET calculations

As shown in Figure 1, the times from when a fire is ignited to detection and from detection to provision of a warnings are the first terms which need to be determined as part of an RSET calculation. Where detection is by an automatic system the time to detection depends upon the fire dynamics and the detection system in place. The time to and type of alarm also depends on the design of the warning system.

Where automatic detection is used to activate a fire protection system, such as a fire suppression system, a smoke control system or a barrier system such as a fire shutter, the timing also depends on the activation systems used for these features, while the effects depend on the system activated.

These systems can have several important effects on ASET and RSET.

The activation of a suppression system, smoke control or barrier effects fire growth and spread, the production of heat and toxic gases, and the layering and spread of smoke, affecting both ASET tenability conditions and RSET escape behaviour.

Detection of fire and activation of fire protection systems constitutes sub-system 4 of [BS 7974](#). Guidance on these aspects was provided by PD 7974-4, but since this has now been withdrawn, different aspects are now provided included in the other documents in the PD 7974 series. Some general aspects relevant to detection and alarm systems are provided here in [Annex A](#). Guidance on other aspects is provided as follows:

- a) detection time (activation of automatic heat detection) in PD 7974-1;
- b) detection time (activation of automatic smoke detection) in PD 7974-2;
- c) activation and performance of smoke control systems in PD 7974-2; and
- d) activation and performance of fire suppression and barrier systems in PD 7974-3.

4.6 Evacuation strategies

Available strategies include simultaneous, phased or progressive evacuation. The selection of a strategy depends upon the building type, fire safety provisions and management philosophy, all of which influence the evacuation time.

Evacuation strategies include the following.

- a) Immediate, simultaneous evacuation of all occupants on sounding of the alarm.
- b) Phased movement of people immediately at risk before movement of others. For this case, the escape route capacity might be insufficient to enable a rapid simultaneous evacuation of the entire building.
- c) Progressive movement of people immediately at risk to a fire (flame and smoke) resisting compartment either vertically or horizontally within a building while monitoring the developing situation before deciding to move others. Where occupants are evacuated from fire threatened areas to protected spaces within a building, especially for tall buildings, a dynamic risk assessment is required. If fire or effluent continues to spread then a total evacuation might become necessary before escape routes become compromised.
- d) Stay put strategy with evacuation of people immediately at risk. Other occupants may remain within a fire (flame and smoke) resisting compartment. Evacuation of other occupants might not normally be necessary. Especially for tall buildings, a dynamic risk assessment is required. If fire or effluent continues to spread then a total evacuation might become necessary before escape routes become compromised.

Planning an evacuation strategy prevents congestion at access and egress locations. Disruption resulting from total evacuation of building occupants in response to a minor fire incident is also an issue. Some strategies consider movement of people only when necessary, for example in hospitals where rapid evacuation of impaired persons might be impractical. Hospital evacuation strategies often involve progressive horizontal movement of occupants to an adjacent fire compartment used as a place of temporary refuge.

NOTE Attention is drawn to Approved Document B [1].

4.7 Margin of safety and accounting for uncertainties

An adequate margin of safety takes account of the risks associated with different types of occupancies and the people likely to use those occupancies, as well as potential fire scenarios and the uncertainties in the prediction of ASET and RSET for particular design scenarios.

Performance-based design relies on engineering calculations for the various time-dependent elements of the design and, in particular, the adequacy of the safety margin depends upon the rigour of the ASET and RSET calculations. It is useful if these calculations show the assumptions made for each step of the fire effluent production and spread, and for each step of the occupant escape

calculations. It is also useful to provide an audit trail for each step, detailing the assumptions made, including assumed ranges of variation and uncertainty.

For deterministic assessments the choices made for specific parameters may be justified, and a number of calculations may be made to demonstrate the effects of variations in key parameters.

When considering adequate margins of safety for ASET and RSET calculations, sources or uncertainty should be taken into account, including the following.

For ASET calculations, uncertainties affecting:

- a) fire development and effluent spread; and
- b) yields of toxic gases and smoke particulates, which depend on the combustion conditions, the composition (especially the elemental composition) of each fuel involved and the proportions of different fuels.

These aspects determine the time-concentration or intensity curves for the fire effluents and heat at the occupant location, and are covered by [BS 7974](#), PD 7974-1, PD 7974-2 and PD 7974-3.

The following aspects determine the effects on occupants in terms of the incapacitating effects of exposure to smoke, heat and toxic effluents on escape capability. These are covered in this Published Document.

- 1) Predicting the incapacitating effects of exposure to smoke. These involve behavioural effects and physical effects. Important variables are the willingness of occupants to enter and move through visually obscure, irritant and toxic smoke, and physical effects on their ability to do so. For behavioural effects, uncertainties arise from the variable psychological and behavioural characteristics of individual occupants and the particular exposure scenario. For physical effects uncertainties relate to walking speed and the physical ability to move through smoke. These have been measured under experimental conditions (see [Clause 10](#)), but not during actual incidents. They show a distribution of effects within an exposed population, with overall trends depending on smoke density and features of the exposure scenario.
- 2) Effects of exposure to asphyxiant gases: uncertainties arise due to sensitivity distributions in the occupant population, which are not fully quantified, and to uncertainties in the accuracy of the incapacitation expressions, which are of necessity derived partly from limited human data and partly from measurements in other species, with inherent uncertainties in extrapolation to humans.
- 3) Predicting the effects of heat exposure: where occupants are exposed to hot smoke or directly to heat (for example while walking past flames). Uncertainties relate to assessment of physical ability to tolerate heat exposure, which depends partly on uncertainties with respect to the heat exposure calculation expressions and the effects of clothing and partly on individual sensitivity.

For RSET calculations, uncertainties associated with each term illustrated in [Figure 1](#), including:

- time to detection, which depends partly on aspects of fire growth and effluent spread (see PD 7974-1 and PD 7974-2), partly on the activation of automatic detection systems and their protocols (see PD 7974-1 and PD 7974-2), and partly on human factors (see this Published Document);
- time to alarm or other warning: depending partly on the protocols for activation of automatic alarm systems (see this Published Document), and partly on human factors (see this Published Document); and
- uncertainties with respect to pre-travel times, walking speeds and evacuation behaviours depend on individual variation and on aspects of the design behavioural scenarios described in this Published Document.

In a design context it is necessary to consider what level of risk threshold is acceptable for each parameter in the ASET – RSET assessment, and in the overall design. For the parameters and expressions described in this Published Document, indications are provided as far as possible on the confidence and limits or distributions for each parameter, to inform the choice of appropriate safety limits or margins. Overall safety margins for the design should then be assessed in accordance with [BS 7974](#).

For any specific set of ASET and RSET calculations, the margin of safety (t_{margin}) is represented by the difference between ASET (t_{ASET}) and RSET (t_{RSET}) as shown in Equation (1).

$$t_{\text{margin}} = t_{\text{ASET}} - t_{\text{RSET}} \quad (1)$$

To allow for uncertainties within each step of calculations application of a safety factor ought to be considered.

Probabilities can also be described as mathematical analysis and therefore consequences as probabilistic. Guidance regarding a probabilistic approach is provided in PD 7974-7.

Safety factors are considered where assumptions have been used due to lack of available data, to allow for distributions in parameters and where the design recognizes challenges and the impact of the effects of fire.

When considering how much margin of safety to apply, it is important to recognize the impact of the fire scenario against which the design is being considered on escape, such as impairment of the means of escape due to the nature, location or other impact of the fire and its effluent. For example, the design might need to discount at least one of the defined exits for its evacuation calculation.

The acceptable margin of safety should be established during the QDR.

4.8 Elements used in quantification of RSET

The basic formula used for determining the escape time for a building is as shown in Equation (2).

$$t_{\text{RSET}} = \Delta t_{\text{det}} + \Delta t_{\text{a}} + (\Delta t_{\text{pre}} + \Delta t_{\text{trav}}) \quad (2)$$

NOTE RSET (escape time) includes all four terms in Equation (2). Evacuation time (t_{evac}) consists of the last two terms of the equation.

Δt_{det} is the time from ignition to detection by an automatic system or first occupant to detect fire cues. This depends upon the fire detection system in place and the fire scenario and is beyond the scope of this Published Document. Guidance on estimation of fire growth characteristics within the enclosure of origin is provided in PD 7974-1 and guidance on detection is provided in PD 7974-1 (heat detection) and PD 7974-2 (smoke detection). The human role in detection and warnings is discussed in [Annex A](#).

Δt_{a} is the time calculation from detection to a general alarm or warning in any specific location. This can vary between effectively zero seconds (where the fire is detected by an automatic system triggering a general alarm on first detection) to several minutes (when for example, staged alarm systems are used or where there is no automatic detection). Guidance on default alarm times for different system configurations is provided in [Annex A](#).

Δt_{pre} is the pre-travel time for occupants of an enclosure. This has two behavioural elements for each individual occupant (recognition and response times). With regard to calculation of the main elements of escape and evacuation times of occupant groups it is important to recognize two phases:

- a) the period between the raising of a general alarm and the travel of the first few occupants: pre-travel time first occupants: $[\Delta t_{\text{pre}(\text{first occupants})}]$; and

- b) the distribution of pre-travel times for the occupant group. This can be expressed as distribution of individual times or represented by a single time such as that of the population mode or the last occupant to move, depending upon the type of analysis: $[\Delta t_{\text{pre(occupant distribution)}}]$.

Further guidance is provided in [Annex B](#).

The quantification of pre-travel times depends upon a wide range of variables. These are discussed in [Clause 5](#) and [Clause 6](#).

Δt_{trav} is the travel time of the enclosure occupants or building occupants, each of which has sub-categories which should be identified and assessed in a design review and incorporated into the performance assessment.

It has two major components.

- 1) The time required for occupants to walk (or move by other means) to an exit leading to a protected escape route: “walking” time $[\Delta t_{\text{trav(walking)}}]$ (see Bensilum and Purser, 2003 [16] and Purser, 2001 [25]. Walking time may be expressed as a distribution of individual times or represented by a single time such as the average time required to walk to the exits, or the time required for the last occupant to walk to an exit. This in turn depends upon the walking speed of each occupant and their distance from an exit. Walking time is determined by the physical dimensions of the building, the distribution of the occupants and their walking speeds. Walking speeds and walking times are dependent upon occupant characteristics such as age, physical ability etc. but also occupant density, since walking is impeded by crowding at high levels of occupant density within the enclosure. Where walking is unimpeded at low densities this represents the minimum time required to walk to the exits.
- 2) The time required for occupants to flow through exits and escape routes: flow time $[\Delta t_{\text{trav(flow)}}]$. Flow time from a single enclosure is determined by the flow capacity of the enclosure exits, providing there are no width restrictions, obstructions or capacity limits causing congestion in further parts of the escape route to the outside. Where there are “downstream” width or capacity limits, or where downstream merges with flows from other enclosure occur then the flow might be limited. Guidance on calculating flows for different situations is given in [Clause 7](#). This can also be evaluated in terms of individual occupants or represented by the total time required for the occupant population to flow through the exits. Flow time represents the time required to evacuate an enclosure assuming all occupants are available at the exits and optimal use of available exits is made.

Walking times and flow times may be used to estimate the times required for an occupant population to enter a protected escape route, such as through storey exits into a protected stair, but may also be applied to travel through escape routes to the final exits of a building.

Travel speed and occupant flow time depend upon influences which are explained in [Clause 7](#) to [Clause 9](#).

A concept found to be useful in the evaluation of evacuation times is that of “presentation time” (Δt_{pres}). Presentation time represents the time from a warning to that when an occupant presents themselves at an exit with the aim of leaving the enclosure, assuming that their progress across the space and through an exit is unimpeded (so that walking speed is unrestricted).

$$\Delta t_{\text{pres}} = \Delta t_{\text{pre}} + \Delta t_{\text{trav(walking)}} \quad (3)$$

Another useful concept is that of time to queue (Δt_{queue}). This represents the time from the raising of a general alarm to that when queues form at the exits. Queue formation occurs when the occupant presentation rate at the exits exceeds the maximum occupant flow rate that can be sustained

through the exits. For a simple estimate the error in assuming time to queue formation is equal to the presentation time of the first percentile¹⁾ has been found to be small.

For groups of occupants both pre-travel time and travel times follow distributions and there is a considerable degree of interaction between the distributions.

Human behaviour is involved to a greater or lesser extent in all these processes, and so each should be evaluated and quantified in a design context. While travel and flow calculation methods are relatively simple and robust, issues relating to occupant behaviour are more complex and difficult to quantify. This Published Document provides practical guidance on how these issues can be addressed in a design context.

5 Design behavioural scenarios for quantification of RSET pre-travel and travel times

5.1 General

In the same way that an engineering design fire scenario is necessary for the quantification of ASET, so an engineering design behavioural scenario is necessary for the quantification of RSET.

The quantification of pre-travel and travel times is highly influenced by aspects of occupant behaviour and, depending upon the systems in place, detection and alarm times can also be influenced by behavioural considerations. In order to deal with this aspect, a method has been developed whereby a set of key qualitative features of occupant behaviour is used to specify a small number of basic “design behavioural scenarios” for different occupancy types analogous to design fire scenarios (see Purser, 2003 [2]).

The occupant behaviours involved in escape depend upon a range of factors including:

- a) building characteristics [particularly occupancy type (purpose group), method for detection and the provision of warnings, fire safety management systems and building layout];
- b) occupant characteristics [particularly occupant numbers, alertness (waking or sleeping) and familiarity with the building and its systems];
- c) fire dynamics – in situations where occupants are exposed to fire effluent (see [BS ISO/TR 13387-8](#) and Purser, 2003 [2]; Canter, 1990 [4]; Sime, 1988 [5] and Bensilum and Purser, 2003 [16]); and
- d) fire intervention effects.

Within each of these categories, there is a wide range of variables which can be considered for any design case. Details of these variables are set out in [Annex C](#).

Although all the occupant and building characteristics can affect escape times, the most important drivers are:

- 1) for occupants:
 - number and distribution;
 - alert/asleep;
 - familiar and trained or unfamiliar;
 - physical ability;
 - cognitive ability;
 - independent evacuation vs. need for assisted evacuation;

¹⁾ Percentile is a measure used in statistics indicating the value below which a given percentage of observations fall.

- 2) for buildings and building systems:
 - warning system;
 - fire safety management and staff/occupant training;
 - single or multiple enclosures and spatial complexity;
- 3) for fire scenarios:
 - fire alarms and cues available to occupants; and
 - features of the fire and fire effluent.

All aspects of these variables should be taken into account for any specific building design as set out in [Annex C](#).

Although some of these factors and their influence on evacuation are quantifiable in any specific building design, other factors, particularly those affecting occupant behaviour, are essentially qualitative (see Purser, 2003 [2] and Bensilum and Purser, 2003 [16]). The variables driving the responses of individual building occupants in emergency situations are complex but, although each individual has a unique experience, when groups of building occupants are considered, a range of common situations and developing scenarios can be identified. These can be of sufficient simplicity that they can be useful in predicting generic evacuation times for design purposes (see Purser, 2003 [2]; Purser, 2003 [3] and Purser and Bensilum, 2001 [7]).

Quantitative data for phases of behaviour, particularly warning and pre-travel times, have been obtained by observations of fire safety management and occupant behaviour during fire incidents and monitored evacuations for the main categories of design behavioural scenarios (see Purser and Bensilum, 2001 [7] and Bensilum and Purser, 2003 [16]). These are then combined with travel time calculations to provide a simple but robust method for the estimation of escape and evacuation times.

Each of these behavioural scenarios is summarized in [Table 1](#). For each, the default time can be derived for alarm and pre-travel times, depending on the safety management strategies (see [5.2.2](#)) and warning system in place.

Table 1 — *Design behavioural scenarios and occupancy types*

Category	Occupant alertness	Occupant familiarity	Occupant density	Enclosures/ complexity	Examples of occupancy types
A	Awake	Familiar	Low or high	One or many	Office or industrial, storage/ warehousing
B1	Awake	Unfamiliar	High	One or few	Shop, restaurant, circulation space
B2	Awake	Unfamiliar	High	One with focal point	Cinema, theatre, classroom
Ci	Asleep – long-term individual occupancy	Familiar	Low	Few	Dwelling – without 24 h on-site management
Cii	Asleep – managed occupancy	Familiar	Low	Few	Serviced flats, halls of residence, etc.
Ciii	Asleep	Unfamiliar	Low	Many	Hotel, hostel
D	Medical care	Unfamiliar	Low	Many	Residential (institutional)
E	Transportation	Unfamiliar	High	Many	Railway station/airport/train/ tunnel

Certain building characteristics are also important, particularly spatial complexity, travel distances, occupancy load factors, exits and escape routes. These mainly affect travel times, but in some situations, pre-travel times. For each behavioural scenario shown, the basic scenarios may be further subdivided into more closely defined scenarios in each class.

For each scenario category shown in [Table 1](#), factors are described affecting occupant behaviour and the time required for various activities to be carried out during different phases of an evacuation. Detailed descriptions of the different categories are provided in [Annex D](#).

Each basic category has certain general requirements and ranges of likely alarm and pre-travel times, and evacuation flow characteristics. Each design behavioural scenario is defined primarily from the perspective of the occupants rather than the building, but a number of examples of occupancy types for each category are shown.

Default alarm times and pre-travel times are derived depending mainly upon the occupant characteristics, fire safety management strategies and warning system in place.

A building can contain enclosures with different design behavioural scenario categories. For example, a hotel is likely to include offices and working areas occupied by staff (Category A), assembly, circulation, restaurant and shopping enclosures occupied by guests (Categories B1 and B2) and guest bedrooms (Category Ciii). There might also be different scenarios at different times of day. All of these scenarios therefore should be taken into account.

It is also possible to define more specific sub-scenarios within each category. Behavioural scenarios are defined by the behavioural characteristics. As part of human behaviour research, data are obtained for response time in a given behavioural scenario. Research findings can be used to inform future designs (see [Annex E](#)).

Behavioural scenarios are intended for the estimation of pre-travel activity times for occupants responding to alarms and not directly exposed to fire effluent. This is likely to represent the majority of occupants of large multi-storey buildings during most fires. The effects on behaviour caused by seeing fire or smoke should also be taken into account in situations where the occupants are in the fire enclosure or become exposed to fire effluent before commencing travel towards an exit. These situations reduce or increase pre-travel times, depending upon the situation (see Purser and Bensilum, 2001 [7] and Purser and Kuipers, 2004 [26]).

These generic scenarios and their characteristics are provided as a starting point for approach to design cases. For any specific design case it is important to describe proposed design scenarios in terms of the main variables considered to affect occupant evacuation behaviours, the estimated warning and pre-travel times for each behavioural scenario sub-category present, and performance requirements for fire safety management before and during an incident. It is also important to provide data from similar cases (including historical evacuation observations and research data from similar designs) to support the estimates made. The design may include required maximum times between first detection and evacuation warnings for affected populations, maximum target pre-travel times and total travel times into protected escape routes for affected enclosures or for whole building evacuations.

5.2 Major behavioural modifiers in each scenario category

5.2.1 Levels

Within each behavioural scenario category, occupant behavioural characteristics, particularly alarm time and pre-travel time distributions, are further dependent upon a range of variables of which three are considered particularly important:

- a) the quality of the alarm system and warning procedures (classified into levels A1 to A3, see [5.2.2](#));
- b) the complexity of the building (classified into levels B1 to B3, see [5.2.3](#)); and
- c) the quality of the fire safety management (classified into levels M1 to M3, see [5.2.4](#)).

5.2.2 Effect of alarm system on pre-travel

The effect of the alarm system on pre-travel is as follows.

- a) Level A1 alarm system: automatic detection throughout the building, activating an immediate general alarm to all occupants of the affected parts of the building.
- b) Level A2 (two stage) alarm system: automatic detection throughout the building providing a pre-alarm to management or security, with a manually activated general warning system sounding throughout occupied areas affected by potential exposure to flames or smoke, and a general alarm after a fixed delay if the pre-alarm is not cancelled.
- c) Level A3 alarm system: local automatic detection and alarm only near the location of the fire or no automatic detection, with a manually activated general warning system sounding throughout all affected occupied areas.

See also [Annex A](#).

NOTE These alarm system levels are designated in relation to effects on times from detection to alarm and their variability. They do not align with the coverage levels specified in BS 5839 (all parts).

5.2.3 Effect of building complexity on evacuation time to a protected escape route

Building complexity affects pre-travel time and time required for wayfinding (searching for a suitable escape route) as follows (see [Annex E](#) for further information).

- a) Building complexity Level B1 (e.g. simple supermarket) represents a simple rectangular single storey building, with one or few enclosures and a simple layout with good visual access, prescriptively designed with short travel distances, and a good level of exit provision with exits leading directly to the outside of the building;
- b) Building complexity Level B2 (e.g. simple multi-storey office block of less than 60 m storey height) represents a simple multi-enclosure (usually multi-storey) building, with most features prescriptively designed and simple internal layouts;
- c) Building complexity Level B3 represents a large complex building (e.g. large building complexes with integration of a number of existing buildings on the same site, common with old hotel or department stores, tall buildings of more than 60 m storey height, also large modern complexes such as leisure centres, shopping centres and airports). Important features are that internal layout and enclosures involve often large and complex spaces so that occupants could be presented with wayfinding difficulties during an evacuation and the management of an evacuation therefore presents particular challenges.

5.2.4 Classification of fire safety management characteristics and effects on evacuation time

In many situations, the time taken to begin the travel phase of an evacuation (i.e. the pre-travel time), and the subsequent conduct of the travel phase, has been found to be very dependent upon the implementation of the fire safety management strategy. This depends upon elements such as staff training and emergency management practice, but is also dependent upon the quality of the tools at the disposal of management to carry out an efficient and timely evacuation. The most important of these tools are the alarm system and certain building features such as those influencing building complexity. In order to assess the influence of fire safety management on evacuation time, a classification system of three levels of fire safety management has been developed. This can be linked with the classification of the alarm system and the classification of the building complexity.

- a) Management Level M1: the normal occupants (staff or residents) should be trained to a high level of fire safety management with good fire prevention and maintenance practice, floor wardens, a well-developed emergency plan and regular drills. For “awake and unfamiliar” there should be a high ratio of trained staff to visitors. The management system and procedures are subject to independent certification, including a regular audit with monitored evacuations for which the performance needs to match the assumed design performance. Security videotapes from any incidents or unwanted alarms are made available for audit under a certification scheme. This level would usually also imply a well-designed building with obvious and easy to use escape routes (to level B1 or at least B2), with automatic detection and alarm systems to a high level of provision (level A1). If the building is used by the public, a voice alarm system should be provided.
- b) Management Level M2: similar to level 1, but have a lower staff ratio and floor wardens might not always be present. There might be no independent audit. Building features may be level B2 or B3 and alarm level A2. The design escape and evacuation times are more conservative than for a Level M1 system.
- c) Management Level M3: representing standard facilities with basic minimum fire safety management. There is no independent audit. The building might be Level B3 and alarm system A3. This is not suitable for a fire-engineered design unless other measures are taken to ensure safety, such as restrictions on fire performance of contents, high levels of passive protection and/or active systems.

NOTE This classification of management levels is designated in terms of estimated effects of incident management on the timing and efficiency of evacuation parameters, including warning times, pre-travel times, exit choice and travel times. It does not relate directly to management as described in other Published Documents and British Standards.

6 Estimation of pre-travel times based on design behavioural scenario

While detection and alarm times can be represented by single numbers, a difficulty with respect to pre-travel and travel times is that each building occupant has their own individual times (see Purser, 2003 [2]; Purser and Bensilum, 2001 [7]; Bensilum and Purser, 2003 [16]; and Purser, 2001 [25]). It is therefore necessary to consider the pre-travel and travel time distributions of groups of occupants, firstly within individual occupied enclosures and then throughout the building and escape routes. A further complication is that within each occupied enclosure, there are interactions between the distributions of pre-travel and travel times for occupant groups, so that the terms cannot be considered directly additive.

Pre-travel time distributions depend primarily upon the design behavioural scenario category and the fire safety management level, with some effect of alarm level and building complexity.

Computer simulations of building evacuations might consider the evacuation time and travel time for each individual occupant. In order to represent a log-normal distribution of pre-travel times within a simulation using an agent-based model, the distribution can be established in terms of the mean and standard deviation of the log-normal distribution. Individual agents are then randomly assigned individual pre-travel times from the distribution (see Bensilum and Purser, 2003 [16]).

However, for hand-calculations it is possible to make an adequate estimation of evacuation times for most situations by considering two main criteria from the pre-travel time distribution:

- a) the pre-travel times of the first few occupants in an enclosure to move (pre-travel time of the 1st percentile of occupants); and
- b) the pre-travel times of the last few occupants to move (99th percentile of occupants).

Data on pre-travel time distributions for different behavioural scenarios are currently limited, but some measured distributions exist.

NOTE See the SFPE Handbook of Fire Protection Engineering [11] and also Purser, 2003 [3]; Purser and Bensilum, 2001 [7]; Proulx and Fahy, 1997 [8]; Proulx and Sime [14]; Gwynne and Boyce, 2015 [15]; Proulx, 2002 [19]; Boyce et al., 1999 [21]; Bellamy and Geter, 1990 [27]; Bryan, 1983 [28]; Fahy and Proulx, 1994 [29]; Purser and Raggio, 1995 [30]; Raggio, 1996 [31]; Proulx et al., 1996 [32]; Proulx et al., 1995 [33]; Proulx et al., 1994 [34]; Purser, 2010 [35]; Fraser-Mitchell, 1996 [36]; and Lovreglio et al., 2019 [37].

Based upon the data available, suggested default values for pre-travel time 1st and 99th percentiles for different design behavioural scenarios are presented in [Annex E](#). The overall findings from the data are that pre-travel times for both the first and last few occupants to move can be very short (a few minutes or less) and predictable when occupants are awake and fire safety management is of a high standard, and much longer and less predictable when fire safety management and warning system are of a lower standard, and in buildings containing occupants who might be sleeping. When estimating pre-travel time distributions, account should be taken of occupants with physical and/or cognitive difficulties.

7 Estimation of travel times

Important aspects of travel times are:

- a) travel times from occupant locations within each individual occupied enclosure to protected escape routes;
- b) travel flow times into protected escape routes; and
- c) travel times through protected escape routes to place of safety and/or the outside of the building for multi-storey or multi-enclosure buildings.

Travel time to a protected escape route for a single enclosure depends upon two main aspects:

- 1) the distance of an occupant to their exit of choice (or the average travel distance to the exits for a group of occupants) and their walking speed; and
- 2) the arrival times of individuals at the exits and the time spent queuing (if any) at the exits (which in turn depends upon the occupant numbers using the exits, the maximum occupant flow capacity of the exits and of subsequent escape routes).

The distance each occupant needs to travel to a protected exit (and the average distance for a group of occupants) depends upon:

- the position of the occupant(s) within the enclosure;
- the size and shape of the enclosure;

- the distribution of available exits; and
- the exit choices of the occupants.

When calculating travel distances and evaluating exit choice it is necessary to consider the availability of each exit with time throughout the fire scenario. If one or more exits become contaminated by fire effluent or blocked by fire it might be necessary to calculate evacuation times using the remainder of the exits available. A commonly used default method is to discount the largest exit (assume that this might be blocked by a fire) and to calculate evacuation times assuming the remainder of exits are available, while a more detailed ASET analysis determines availability at different times.

NOTE Attention is drawn to Approved Document B [1].

A finding from evacuation experiments and incident reports with respect to choice of available exits is that occupants tend to favour exiting by the same route they entered the enclosure or building. It is therefore prudent to assume a greater proportion of occupants using this route if it is available. For example, following investigation of the Station nightclub fire, NIST recommended that the minimum capacity of the main entrance should accommodate 2/3rds of the maximum permitted occupancy, especially for public access buildings (see Grosshandler et al., 2005 [38]). Travel distances should reflect the internal layout of a building (with partitions, furniture, fixtures and fittings) rather than direct distance for an empty building shell.

Guidance on estimating travel distances to exits for occupant populations is provided in [Annex F](#).

A good representation of travel times to exits for occupant populations can be obtained using agent-based computer simulation models. Simplified estimates can be used for algebraic calculations without significant error. In practice for evacuation calculations it can be assumed that travel of occupants to storey exits is unrestricted (unaffected by crowding). See [Clause 8](#).

For individual occupants, aspects such as physical or cognitive capability (see [Annex G](#)), or time spent in wayfinding and decision making on the way to an exit, or in crowds, can also affect travel time to the exit, especially in large or complex enclosures.

In multi-storey or other multi-enclosure buildings, it is necessary to evaluate occupant flows through horizontal and vertical escape routes, which usually involves merging of flows from different enclosures in corridors or stairs. Where several enclosures are evacuated simultaneously into a protected escape route such as a stair, and the occupant capacity of the stair between floors is less than the number of occupants entering the stair at each floor, then flow into the stair at each floor is limited by merging. For a 50:50 merge ratio the rate of clearance of each floor is approximately halved at each successively higher floor (except the top floor). For buildings designed for phased evacuation, evacuation times for the fire floor may be increased if the floor above or below are also evacuated simultaneously, due to congestion in the stair and merging behaviour at the storey exits.

Guidance on horizontal and vertical travel speeds, and the effects of occupant density, is provided in [Annex G](#). These can be influenced by the presence of occupants with limited mobility, by obstructions in the stair or by the presence of smoke and irritants.

In practice, when groups of occupants evacuate an enclosure, the occupant density increases rapidly near the exits, so that queues form and the subsequent evacuation time depends upon the maximum flow capacity of the exits and subsequent escape routes.

Guidance on queue formation and exit flow capacity is provided in [Annex G](#) and [Annex H](#).

Guidance on effects of smoke density on travel speed is provided in [Annex I](#).

8 Interactions between pre-travel time, walking time and exit flow time for evacuation time calculations

Since pre-travel time for a group of occupants in an enclosure follows a distribution, there is a considerable degree of interaction between pre-travel times, walking times [$\Delta t_{\text{trav(walking)}}$] and exit flow times. For a detailed analysis of evacuation time it is necessary to consider the location of each individual occupant, their individual pre-travel, walking speeds and walking times, the effects of occupant density on walking times and the flow times through the chosen exits. It is possible to carry out such analyses using agent-based computer evacuation simulation methods (see Bensilum and Purser, 2003 [16]; Thompson and Marchant, 1995 [20]; Fraser-Mitchell, 1996 [36]; and Galea et al., 1998 [39]).

In practice, it is possible to reduce such complex interactions to simple calculations without incurring a significant error. This can be achieved for any individual building enclosure by considering two simple cases, providing the key parameters affecting outcomes are identified and adequately considered.

- A case where the enclosure is sparsely populated with a population density of less than one third of the design population. For a sparsely occupied enclosure, where the flow capacity of the exits is high compared to the number of occupants using them, the main drivers of evacuation time are the pre-travel time of the last few occupants to leave and their walking time to the exits. Since the enclosure is sparsely occupied it can be assumed that walking speeds are unaffected by crowding so are unrestricted. Since the flow capacity of the exits is not exceeded, queuing is unlikely to occur at the exits.
- A case where the enclosure contains the maximum design population. For densely occupied enclosures, the main drivers of evacuation time are the pre-travel time of the first few occupants to leave and establish queues at the exits, plus the time required for the occupant population to flow through the exits.

For both cases, it is necessary to consider discounting the largest exit.

NOTE See Purser, 2003 [3] and Purser, 2001 [25].

For cases involving the evacuation of only one enclosure with no downstream restriction on the escape routes, then the maximum flow capacity is limited by the exit widths. For cases with downstream width or capacity restrictions, or for scenarios involving downstream congestion (for example, due to merging flows), then the maximum flow capacity at the exits might be lower than the maximum nominal flows.

For the sparsely populated case the evacuation time depends upon the pre-travel time of the last few occupants to decide to leave and the time required for them to travel to the exits and walk through. Since the occupant density is low the walking speed to the exits is essentially unimpeded and there is no queuing at the exits. Evacuation time is then given by Equation (4):

$$\Delta t_{\text{evac}} = \Delta t_{\text{pre(99th percentile)}} + \Delta t_{\text{trav(walking)}} \quad (4)$$

where:

$\Delta t_{\text{pre(99th percentile)}}$	is the time from alarm to movement of last few occupants (from Table E.2);
$\Delta t_{\text{trav(walking)}}$	is the walking time (the unimpeded walking speed multiplied by average travel distance to exits). (A conservative estimate could use the maximum direct travel distance for the enclosure.)

For the fully occupied case the evacuation time depends upon the pre-travel and walking time of the first few occupants plus the flow time of the exits, which is given by Equation (5):

$$\Delta t_{\text{evac}} = \Delta t_{\text{pre}(1\text{st percentile})} + \Delta t_{\text{trav}(\text{walking})} + \Delta t_{\text{trav}(\text{flow})} \quad (5)$$

where:

$\Delta t_{\text{trav}(\text{flow})}$ is the time of total occupant population to flow through available exits.

In the fully occupied case it is possible that the walking speed of the first occupant to move could be restricted by other occupants and/or objects nearby, but the most likely scenario is that the first to move would be closer to the exits and relatively unrestricted, so that uncertainty from assuming unrestricted walking speed is likely to have a negligible effect on the calculated total evacuation time.

Of the two calculated cases, the one with the longest evacuation time should be used for design purposes and, in most scenarios, the second case would represent the longest evacuation times.

[Annex H](#) contains guidance on simple calculation methods and a worked example from a computer simulation of an evacuation case showing the interactions between pre-travel times, walking times and exit flow time and their influence on evacuation time.

9 Calculation of escape and evacuation times for single enclosures and for multi-storey or multi-enclosure buildings

For situations where occupant exit choice and travel speed is affected by smoke exposure these effects should be assessed in accordance with the guidance in [Clause 10](#) and [Annex I](#).

A series of generic worked examples of the application of the method for calculating escape (RSET) and evacuation times for single enclosures involving different design behavioural scenario cases is presented in [Annex J](#).

The escape and evacuation time calculation methods described apply to any individual occupied enclosure within a building, giving the time required to evacuate the occupants into a protected escape route. When an evacuation involves simultaneous evacuation of more than one enclosure into an escape route such as a corridor or stair, then the time to evacuate depends upon the flow capacity of the escape route and the proportions in which the flows from different enclosures merge. Calculation of times to clear individual enclosures cannot then be carried out simply using hand calculations and is best done using computer simulation models. The flow rate of occupants from individual enclosures depends upon the ratio of the merging flows at the landings of the escape stairs with occupants from other enclosures and on the flow capacity of the stairs.

As with single enclosures, the main drivers of evacuation times for multi-enclosure buildings depend to some extent upon the occupant numbers. Where the number of occupants evacuating is small compared with the flow capacity of the escape routes (such as in some low rise office buildings), or in situations where the pre-travel distribution is very wide (such as is likely to be the case in sleeping accommodation at night), then the flow capacity of the escape routes is unlikely to be exceeded and evacuation time depends upon the pre-travel time of the last few occupants to leave, their walking speeds and the travel distance to the final building exits.

For more densely occupied multi-storey buildings during simultaneous evacuation of several floors (or the entire building), evacuation times depend upon the pre-travel time of the first occupants to enter the stairs plus the flow time into and down the stairs. In experimental and modelling studies (see Purser and Gwynne, 2007 [22], Boyce et al., 2012 [23] and Purser and Boyce, 2009 [24]), the

travel time to clear each floor of multi-storey buildings into a protected stair has been found to be very dependent upon three parameters.

- a) The maximum flow rates through storey exits, on stairs and through final exits.
- b) The “standing” capacity of the stair between storeys, which for a given stair depends upon standing area of the stairs and landings, and the “packing” density taken up by the occupants as they descend the stair.
- c) The merge ratio at the storey exits between occupants on the stair and those from the floor.

Where several stairs are available, the distribution of the evacuating population between different stairs (or between stairs and elevators) can also affect the extent of congestion on different stairs and hence the evacuation time.

Guidance on maximum flow rates through horizontal and vertical escape routes is presented in Gwynne and Rosenbaum’s chapter in the *SFPE Handbook* [18] (see [Annex G](#) for further details). The standing area on a stair depends upon the building design. Little guidance is available regarding occupant densities on stairs, but the densities obtained in these experiments were found to be quite low (approximately 2 persons/m²) under crowded conditions with slow flows (see Purser and Gwynne, 2007 [22], Boyce et al., 2012 [23] and Purser and Boyce, 2009 [24] and Kuligowski et al., 2014 [40]).

Merge ratio data are limited, but three main assumptions often used are:

- 1) flow dominated by occupants on the stair – building empties from the top floor down;
- 2) occupants on the stair “defer” to occupants at storey exits – building empties from the bottom up; and
- 3) merge ratio around 50:50 at storey exits – building empties from the bottom up.

For situations where the different floors of a building are sparsely occupied so flows at storey exits are well below maximum, then merging of occupants at storey exits is unrestricted and occurs at the rates and ratios of arrival at the merge points.

For more crowded situations, where occupancy levels approach the design maximum, then merging behaviour can have a considerable influence on the pattern of evacuation from a tall building. If the flow on the stair from an upper floor merges equally with the flow from the floor below, the flow rate from each floor will be half the maximum flow rate on the stair descending to the next level, in crowded situations. If the flow of occupants in a stairwell from the upper floor dominates, occupants from the lower floors cannot evacuate until those from the upper floor have gone. This is the basis of the method used to calculate evacuation times for multi-storey buildings described in Gwynne and Rosenbaum’s chapter in the *SFPE Handbook* [18]. In other building configurations, various degrees of merging flows are likely to occur. In some cases, deference behaviour can occur, whereby occupants descending the stairs give preference to occupants entering the stair from the storey exits. In such situations the lower floors of the building clear first, so that those on the upper floors can be delayed (see Proulx, 2002 [19]).

In computer simulations and experimental evacuations involving crowded conditions, merge ratios have been found to approximate to 50:50 for a variety of different buildings and stair layouts (see Purser and Gwynne, 2007 [22]). This also can result in the lower floors clearing first, with clearance rates approximately halving at progressively higher floors. This is especially the case if the number of occupants on each floor exceeds the standing capacity of the stairs between floors.

Occupant flows on stairs can also be affected to some extent by counterflows or partial blockages (for example of fire service personnel ascending a stair or deploying equipment in a stair), or by the range of physical abilities of the evacuating population (especially in very tall buildings).

Another consideration is the time required for total evacuation of a multi-storey building. Once occupants have begun to evacuate, this depends upon the flow capacity of the available stairs and the population using them. The time required for a given population to evacuate a building using a specific stair (and hence for total evacuation of a building using all available stairs) can be calculated using computer simulations. Simple calculations can also be used to provide an accurate estimate of the travel component for total evacuation of a multi-storey building (see [Annex G](#)). The time should be assessed for which a stair remains available for escape in case of fire, and for which an exit to that stair remains accessible on each floor. This might depend partly on whether or not it is protected by lobbies.

NOTE Attention is drawn to Approved Document B [1].

Consideration should also be given to the extent that the building population would make use of different stairs to escape.

Pauls in Proulx, 2002 [19] developed Equation (6) from 50 experimental high rise building evacuations by stairs. The predictive curve has a net error in predicting total simultaneous evacuation travel times in buildings of 8 to 15 storeys of 0.2%.

$$T = 0.68 + 0.081p^{0.73} \quad (6)$$

where:

T is the minimum time (minutes) to complete an uncontrolled total evacuation by stairs;

p is the actual evacuation population per metre of effective stair width (actual width minus 0.3 m).

Although this expression is useful for a first approximation, caution is required when applying it to modern populations due to demographic changes in age, bodyweight and ability distributions since this work was carried out.

The dynamics of interactions between pre-travel distributions on different floors, and patterns of congestion and flows on stairs, can vary when wide variations occur in warning and pre-travel times and distributions on different floors of tall buildings (see Galea et al., 2007 [41]). Effects on evacuation via protected stairs resulting from fire development, such as contamination by fire effluent, fire penetration or structural damage might need to be considered in relation to the fire simulation dynamics.

For some designs, lifts may be included in the emergency evacuation strategy.

Temporary safe refuges may be provided on each floor for persons of limited physical ability who are unable to evacuate using a stair. Where these are in a lobby containing a suitably designed lift, then this can provide a safe and effective means of escape for these occupants.

Advice, signage and training may be used to prioritize evacuation (including self-evacuation) of relevant persons using the lifts.

Where lifts are included as part of the general evacuation strategy then the evacuation flows using the lifts may be included with those using the stairs for overall ASET-RSET calculations.

A variety of lift operation protocols are used in different buildings for call, pick-up and discharge at different floors. Calculations of evacuation timing and flows from different floors therefore depend on the specific design.

NOTE Details of requirements for lifts and their use in emergency evacuations are not dealt with in this document. For guidance concerning lifts, see [PD ISO/TR 25743](#), [PD ISO/TR 16765](#), [BS EN 81-72](#) and [BS EN 81-73](#).

10 Occupant condition

10.1 Effects of fire effluent and heat on ASET and RSET

Exposure of building occupants to fire effluent or heat affects both ASET and RSET. These depend on:

- a) the time-concentration (or intensity) curves for the major toxic products, optically dense smoke and heat in the fire at the breathing zone of the occupants, which in turn depend upon:
 - 1) the fire growth curve in terms of the mass loss rate of the fuel (kg/s) and the volume into which it is dispersed (kg/m³) with time;
 - 2) the yield of toxic products, smoke and heat generated in the fire (for example kg CO per kg of material burned).

Guidance on calculation methods for these terms is given in PD 7974-1, PD 7974-2 and PD 7974-3.

- b) the toxic or physiological potency of the heat and effluent [the exposure concentration (kg/m³), or exposure dose (kg·m⁻³·min or µl·l⁻¹·min) required to cause toxic effects (and the equivalent effects of heat and smoke obscuration)].

The determination of ASET requires consideration of three aspects:

- exposure concentrations or doses likely to impair or reduce the efficiency of egress due to psychological and/or physiological effects;
- exposure concentrations or doses likely to produce incapacitation or prevent egress due to psychological and/or physiological effects; and
- lethal exposure concentrations or doses.

Guidance on calculation methods for this term is presented in [Annex I](#), in [BS 7899-2](#) and in Purser, 2016 [42] and Purser and McAllister, 2016 [43].

The endpoint of an ASET calculation is the time when conditions in each building enclosure are considered untenable. Untenable conditions occur when it is predicted that an occupant inside or entering an enclosure is likely to be unable to save themselves (is effectively incapacitated) due to the effects of exposure to toxic products, smoke particulates and heat.

The psychological and physiological effects of exposure to toxic products, smoke particulates and heat in fires combine to cause varying effects on escape capability, which can lead to physical incapacitation and permanent injury or death.

Behaviour modifying or incapacitating effects include:

- 1) effects of seeing smoke or flames including:
 - fear of approaching smoke, flames or heat-logged areas or escape routes;
 - fear of fire or smoke in an occupied compartment. This can act as a stimulus to escape or a barrier to escape, depending upon the location and intensity of the fire or smoke;
 - attraction towards fire in an occupied compartment (friendly fire syndrome) to observe or tackle fire;
- 2) impaired vision resulting from the optical density of smoke and from the painful effects of irritant smoke products and heat on the eyes;
- 3) respiratory tract pain and breathing difficulties or even respiratory tract injury resulting from the inhalation of irritant and/or hot smoke. In extreme cases, this can lead to collapse within a few minutes from asphyxia due to laryngeal spasm and/or broncho-constriction (particularly in

asthmatics and other sensitive occupants). Lung inflammation can also occur, usually after some hours, which can also lead to varying degrees of respiratory distress;

- 4) asphyxiation from the inhalation of toxic gases and/or oxygen-depleted air resulting in confusion and loss of consciousness (particularly in sensitive occupants such as the elderly and those with heart disease); and
- 5) pain to exposed skin and the upper respiratory tract followed by burns, or hyperthermia, due to the effects of heat, preventing escape and leading to collapse.

All of these effects can impair escape or lead to permanent injury, and all except 1) and 2) can be fatal if the degree of exposure is sufficient.

With regard to hazard assessment and tenability criteria, the major considerations with respect to means of escape and life safety are as follows:

- the psychological effects of seeing fire effluents on escape behaviour in the absence of direct exposure;
- the psychological and physiological effects of exposure to heat and toxic smoke on escape behaviour and ability;
- the point where exposure results in incapacitation; and
- the point where exposure results in death.

In a design context, the important considerations with respect to psychological and physiological considerations are to set reasonable tenability limits for occupants to remain in a place of safety or to use a particular escape route, and to determine the likely effects of any exposure sustained on escape capability and subsequent health.

For a full performance-based analysis it is possible to assess both ASET and RSET, and the consequences to exposed populations of more prolonged exposure to more extreme conditions in order to assess the consequences of different scenarios, for both deterministic and probabilistic analyses. In order to evaluate the suitability of a design for specific scenarios it is often possible to apply simpler criteria using relatively conservative tenability limits without the need for a full analysis. Approaches for different scenarios are described in the following sections.

10.2 Simple criteria for tenability based upon zero smoke exposure and tolerable heat exposure

Where a design fire calculation is based upon a descending upper layer of hot smoke filling an enclosure or escape route, engineering tenability criteria are often based upon a minimum clear layer height of 2.5 m above the floor and a maximum upper layer temperature of 200 °C. Occupants are considered to be willing and able to escape in clear air under such a layer and the downwards heat radiation is considered tolerable.

10.3 Simple criteria for tenability based on minimal exposure to smoke and heat

Where smoke is mixed down to floor level but visibility is >5 m (for reflective objects or signage), escaping occupants do not have to pass flames, heat radiation is <2.0 kW/m² or temperature is <115 °C, at occupant head level, then conditions can be considered tenable for escape within specified time limits. Based on typical ratios of smoke density to toxic gases (see PD 7974-1:2019, Annex B and Purser, 2016 [42]) it is also possible to estimate limits for irritant and asphyxiant effects of toxic gases from smoke optical density, and from heat as follows.

For smoke with a visibility of >10 m (D/m ~1) the concentrations of toxic gases are tolerable for up to 1 hr and enable wayfinding to exits in large buildings.