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Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people

Ingénierie de la sécurité incendie — Informations techniques sur les méthodes d'évaluation du comportement et du mouvement des personnes

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Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 16738 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

This Technical Report provides information (sometimes called "advice" or "guidance", although there is no intention to present mandatory guidance) on engineering methods currently available for the evaluation of life-safety aspects of a fire-safety engineering design for the built environment, including structures such as tunnels, underground complexes, ships and vehicles. Advice is presented on the evaluation and management of occupant behaviour, particularly escape behaviour, during a fire emergency and for the evaluation of occupant condition and capabilities, particularly in relation to the effects of exposure to fire effluent and heat.

The guidance focuses mainly on the evacuation of the occupants, although maintenance in place or relocation to an area of refuge or safety can be appropriate alternatives in some situations. A basic principle of performance-based (fire-safety engineering) design is that the available safe-escape time (ASET) is greater than the required safe-escape time (RSET) by an adequate margin of safety.

Should a fire occur in which occupants can be exposed to fire effluent and/or heat, the objective of the fire safety engineering strategy is usually to ensure that such exposure does not significantly impede or prevent the safe escape (if required) of all of the occupants, without their experiencing or developing serious health effects.

Possible objectives for a fire-safety design can include ensuring that those occupants outside the area of fire origin are able to reach (or remain in) an area of safety without ever coming into contact with, or even being aware of, fire effluent and/or heat, while those inside the enclosure of fire origin are not subjected to life-threatening conditions. These are proposed as the main design criteria for the safety of the majority of occupants in multi-compartment structures.

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

In order to achieve these evaluations, detailed input information is required in four main areas:

— building design and emergency life safety management strategy;

— occupant characteristics;

— fire simulation dynamics;

— intervention effects.

The response of occupants to a fire condition is influenced by a whole 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; and the interaction of all these features with the developing fire scenario and provisions for emergency intervention (fire brigade and rescue facilities).

Guidance is provided on

a) the evaluation of escape and evacuation times from buildings:

   — for occupants not directly affected by fire (for example, in building locations remote from the fire compartment),

— for occupants whose escape behaviour and, therefore RSET, is influenced by fire effluents and heat;

b) the evaluation of ASET in relation to tenability limits due to fire effluents and heat.

NOTE Reference can be made to ISO 13571 for details of calculation methods used for the evaluation of tenability in relation to exposure to fire effluent and heat.

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

— time from ignition to detection;

— time from detection to the provision of a general evacuation warning to occupants;

— evacuation time, which has two major phases:

  — pre-travel activity time, which consists of the time required to recognize the emergency and then carry out a range of activities before the evacuation travel phase,

  — travel time (the time required for occupants to travel to a safe location).

Time from ignition to detection and from ignition to alarm are covered in ISO/TR 13387-7. In terms of pre-travel activity time recognition and response times, most research (see References [1], [2], [3], [4], 5], [6], [7], [8] and also ISO/TR 13387-8) has been essentially qualitative, describing the psychological, behavioural and physiological factors affecting detection and recognition of fires and the wide range of behaviours engaged in by groups of occupants. There are few methods available for the quantification of these phenomena and the interactions between them, although some data on response time distributions have been obtained from observations of behaviour during real or simulated emergencies; see References [4], [5] and [9]. These studies have shown that the overall times required for these behaviours can comprise the greatest part of the time required for escape.

Travel to and through exits and escape routes involves more physically based processes, which have been relatively well quantified and are amenable to relatively simple calculation methods for design purposes; see References [10], [11], [12] and [13]. Nevertheless, travel times can be affected by behaviours such as way-finding and exit choice. Also, certain physical phenomena, such as merging flows, have not been adequately evaluated; see References [11] and [14].

There are considerable interactions between the various aspects of pre-travel activity time and travel times in the determination of total evacuation times for groups of building occupants. This has considerable implications for design performance evaluations; see References [6], [14], [15] and [16].

It is expected that users of this Technical Report are appropriately qualified and competent in the fields of fire-safety engineering and fire risk assessment. It is particularly important that users understand the parameters within which particular methodologies can be used. Users are cautioned that methods developed for, and assumptions based on observations from, building evacuations might not be directly applicable to different occupancies or to other built environments, such as tunnels or ships.

Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people

1 Scope

This Technical Report is intended to provide information to designers, regulators and fire safety professionals on the engineering methods available for evacuation strategies in relation to the evaluation of life safety aspects of a fire safety engineering design. Information is presented on the evaluation, quantification and management of occupant behaviour, particularly escape behaviour, during a fire emergency.

This Technical Report addresses the parameters that underlie the basic principles of designing for life safety and provides information on the processes, assessments and calculations necessary to determine the location and condition of the occupants of the building, with respect to time.

This Technical Report provides information on methods for the quantification of the different aspects of human evacuation behaviour in a design context. It is intended for use together with the parts of ISO/TR 13387 and associated guidance documents and standards. These provide some of the information useful in performing a life safety evaluation and a means for incorporating the results of the life safety evaluation into the wider aspects of a fire safety engineering design.

The use of lifts (elevators) in emergency evacuations is not dealt with in this Technical Report.

2 Normative references

The following referenced documents are indispensable for the application 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.

ISO/TR 13387-8, *Fire safety engineering — Part 8: Life safety — Occupant behaviour, location and condition*

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TR 13387-8 and ISO 13943 and the following apply.

NOTE It has been necessary to produce a number of new terms to identify particular elements of behaviour useful in the quantification of escape and evacuation times.

3.1
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

3.2
escape route
path forming that part of the means of escape from any point in a building to a final exit or other safe location

3.3
escape time
interval between ignition and the time at which all occupants are able to reach a safe location

3.4
exit
doorway or other suitable opening giving access towards a place of relative safety

3.5
flow time
time required for a group of occupants to pass through a specific exit or set of exits from an enclosure or building

3.6
margin of safety
extra 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.

3.7
management
person or persons (or their actions) in overall control of the premises whilst people are present, exercising this responsibility either in their own right, e.g. as the owner, or by delegation (of statutory duty)

3.8
merge ratio
ratio of the number of lanes of flow upstream and the number of lanes of flow downstream after flows have reached a merge point or shared space; or the proportional share of downstream flow accounted for by flows that have met at merge points

3.9
pre-travel activity time
PTAT
interval between the time at which a warning of a fire is given and the time at which the first move is made by an occupant towards an exit

NOTE 1 This consists of two components: **recognition time** (3.10) and **response time** (3.11).

NOTE 2 For groups of occupants, two phases can be recognized:

— pre-travel activity time of the first occupants to move;

— pre-travel activity time distribution between the first and last occupants to move.

3.10
recognition time
interval between the time at which a warning of a fire is given and the first response to the warning

3.11
response time
interval between the time at which the first response to the event occurs and the time at which travel begins to a safe location

3.12
safe location
location remote or separated from the effects of a fire so that such effects no longer pose a threat

NOTE The safe location may be inside or outside the building depending upon the evacuation strategy

3.13
tenability criteria
maximum exposure to hazards from a fire that can be tolerated without causing incapacitation

3.14
travel time
time needed, once movement towards an exit has begun, for an occupant of a specified part of a building to reach a safe location

3.15
walking speed
unrestricted speed of movement of a person

3.16
walking time
time taken for a person to walk from their starting position to the nearest exit

3.17
warning time
interval between detection of the fire and the time at which a general alarm or other warning is provided to all occupants in a specified space in a building

4 Symbols

t_{ASET} available safe-escape time

t_{RSET} required safe-escape time

t_{evac} time for evacuation

t_{det} time to detection

t_{warn} time to a general alarm or warning

t_{pre} pre-travel activity time

t_{trav} travel time

$t_{trav\ (walking)}$ walking time during travel time

$t_{trav\ (flow)}$ time required to flow through the exits

t_{rec} recognition time

t_{res} response time

t_{marg} adequate margin of safety

5 Integration of behaviour and movement into performance-based design

5.1 General

In most systems of fire safety regulation, measures are taken to ensure the life safety of the occupants by prevention of ignition, prevention of rapid fire spread, provision of facilities and access for fire brigades, provision of detection and warning systems and adequate means of escape. These are often applied through prescriptive means covered by documents and codes relating to national legislative requirements.

The fire safety engineering approach adopted in ISO/TR 13387 (all parts) considers a performance-based approach to achieve a global objective of fire-safe design. The global design, described in more detail in the framework document ISO/TR 13387-1, is subdivided into a series of subsystems. One principle is that inter-relationships and inter-dependencies of the various subsystems are appreciated and that the consequence of all the considerations taking place in any one subsystem are identified and realized.

Another principle is that the evacuation is time-based to reflect the fact that real fires vary in growth rate and spread with time. Despite this performance-based approach, it has to be recognized that it can be necessary to observe some prescriptive parameters in any assessment of the life safety provisions within a building.

5.2 Basis of performance-based design for life safety

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

— adequate escape route provision (number and width of exits and protected escape routes, travel distances to an exit);

— estimates and controls on occupant number and density (e.g. floor-space factors);

— fire separation (passive protection between compartments, passive protection of escape routes, fire and smoke doors and lobbies);

— provision of warnings (manual or automatic detection and alarm system, fire-safety management);

— active fire protection (sprinklers, smoke extraction);

— signage, emergency lighting, etc.

Performance-based (FSE) design evaluation depends on a time-based comparison of the time available for occupants to escape (if necessary) or to reach a safe location (ASET) and the time required for escape (RSET).

5.3 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 of the occupants. Therefore, there is for each space an available safe-escape time (ASET) for the occupants to evacuate to a safe location, before the onset of untenable conditions. 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.

The prediction of ASETs requires estimation of the time-concentration (or intensity) curves for the major toxic products, smoke and heat in a fire (see ISO/TR 13387-2, ISO/TR 13387-3, ISO/TR 13387-4, ISO/TR 13387-5, ISO 16732 and ISO 16733) and the derivation and estimation of ASET endpoints for these hazards (see ISO 13571 for details).

5.4 RSET calculations

Escape time depends on a range of parameters related to detection, the provision of warnings, occupant escape behaviour and movement. The characterization and determination of escape behaviours can be simplified in terms of two broad categories:

a) Pre-travel activity behaviours, sometimes knows as pre-movement behaviours: those involved in the responses of occupants before they start to move through escape routes.

   Although pre-travel activity behaviours can 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 activity phase can often comprise the longest part of the total escape time; see References [2], [5], 6], [9] and [15].

b) Travel behaviours: those involved in physical movement of occupants into and through escape routes.

   Where it is predicted that occupants see fire or smoke during an evacuation or are exposed to heat or fire effluent, their pre-travel activity and travel behaviours can be affected. In this case, it is necessary to take the fire condition data (see Clause 6) into account. Guidance relative to the effects of the fire condition on RSET are provided in this Technical Report.

A simplified diagram 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.

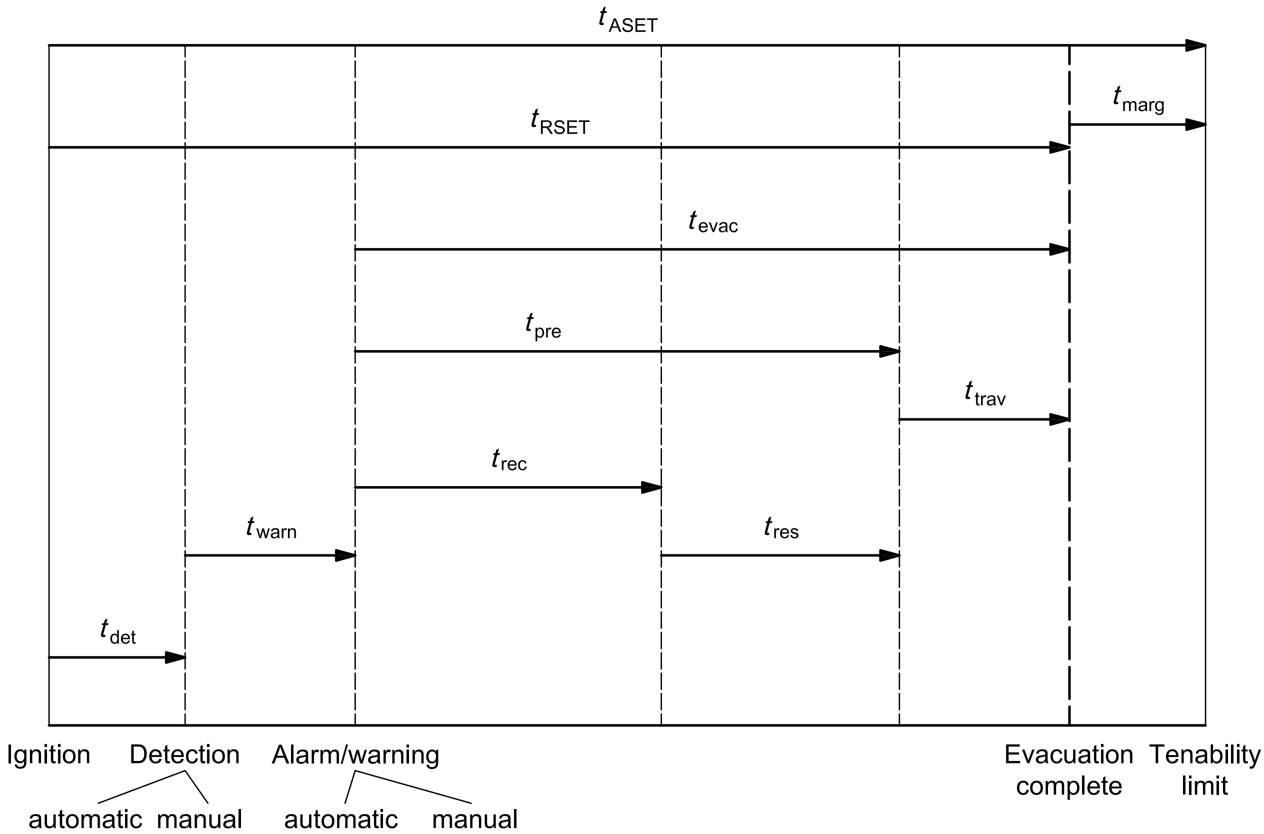


Figure 1 — Simplified diagram of processes in required safe-escape time compared to available safe-escape time

5.5 Evacuation strategies

Evacuation strategy can have a large effect on evacuation times. Simultaneous evacuation of all occupants on detection of a fire is often not the preferred (or possible) initial course of action for many buildings and occupancy types. For many large buildings, phased evacuation strategies are used, whereby occupants are evacuated progressively from parts of a building threatened by fire. For such buildings, the escape route capacity can be insufficient for a rapid simultaneous evacuation of the entire building.

The disruption resulting from total evacuation of a large building in response to a minor fire incident is also an issue. In some countries, for flats and maisonettes for example, the design strategy is to evacuate only the compartment of fire origin and adjacent areas affected by the fire. For buildings such as hospitals, rapid evacuation can be impractical. A strategy of progressive horizontal evacuation is often used, whereby occupants are evacuated to an adjacent compartment as a place of temporary refuge. Even when a strategy of immediate simultaneous evacuation is used, the time required for evacuation can be long (up to approximately an hour) for some occupancies, particularly those involving sleeping accommodation.

5.6 Margin of safety

5.6.1 General

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.

5.6.2 Performance-based design

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.

Guidance on probabilistic approaches for dealing with uncertainty is provided in ISO/TS 16732.

5.6.3 Deterministic design

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.

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

$$t_{\mathrm{marg}} = t_{\mathrm{ASET}} - t_{\mathrm{RSET}} \quad (1)$$

5.6.4 Impact of fire scenario

In considering the margin of safety provided by a design, it is important to recognize the impact that the fire scenario, against which the design is being considered, can have on any of the provisions related to means of escape. It can be important to consider that some of the elements provided might not be available due to the nature, location or other impact of the fire and its effluent, and to take this into account.

5.7 Elements used in the quantification of RSET

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

$$t_{\mathrm{RSET}} = t_{\mathrm{det}} + t_{\mathrm{warn}} + (t_{\mathrm{pre}} + t_{\mathrm{trav}}) \quad (2)$$

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

The time from ignition to detection, t_{det}, by an automatic system or by the first occupant to detect fire cues, depends on the fire-detection system in place and the fire scenario. Guidance on estimation of fire-growth characteristics within the enclosure of origin is provided in ISO/TR 13387-1, ISO/TR 13387-2, ISO/TR 13387-3, ISO/TR 13387-4 and ISO/TR 13387-5, and guidance on detection by mechanical and electrical systems is provided in ISO/TR 13387-7. The human role in detection and warnings is discussed in Annex A.

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

Pre-travel activity time, t_{pre}, has two behavioural elements for each individual occupant, recognition and response times, which are addressed in some evacuation models. Further guidance on pre-travel activity behaviours is provided in Annex B. However, with regard to the main elements of escape and evacuation times of occupant groups, it is important to recognize two phases:

— period between the raising of a general alarm and the travel of the first few occupants: pre-travel activity time of the first occupants, $t_{pre\ (first\ occupants)}$;

— subsequent distribution of pre-travel activity times for the occupant group $t_{pre\ (occupant\ distribution)}$, which can be expressed as a 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.

The quantification of pre-travel activity times depends upon a wide range of variables. These are discussed in Clauses 6 and 7.

The travel time of the enclosure occupants or building occupants, t_{trav}, has sub-categories which it is necessary to identify and assess in a design review and incorporate into the performance assessment.

It has two major components.

— The time required for occupants to walk to an exit leading to a protected escape route is the walking time, $t_{trav\ (walking)}$. 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 on 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 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.

— The time required for occupants to flow through exits and escape routes is the flow time, $t_{trav\ (flow)}$, which is determined by the flow capacity of the exits. 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 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 stairwell, but it may also be applied to travel through escape routes to the final exits of a building.

The quantification of travel speeds and flow rates depends upon a range of variables. These are discussed in Clauses 6, 8 and 9.

A concept found useful in the evaluation of evacuation times is that of “presentation time”. Presentation time represents the time from a warning to that when an occupant presents himself/herself at an exit with the aim of leaving the enclosure, assuming that the person's progress across the space and through an exit is unimpeded (so that walking speed is unrestricted).

Another important concept is that of time to queue, t_{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 groups of occupants both PTAT 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 it is necessary to consider and quantify each 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. A major aim of this Technical Report is to provide practical guidance on how these issues may be addressed in a design context.

6 Design behavioural scenarios for quantification of RSET

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

The quantification of pre-travel activity 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 develop a design behavioural scenario (or scenarios) for any particular occupied structure, it is necessary to consider the occupant behaviours involved in escape, which depend upon a range of factors including

— building (or other structure) characteristics, particularly occupancy type, method for detection, the provision of warnings, fire safety management systems and building layout;

— occupant characteristics, particularly occupant numbers, physical abilities, alertness (waking or sleeping) and familiarity with the building and its systems;

— fire dynamics (see ISO/TR 13387-8), in situations where occupants are exposed to fire effluent;

— fire intervention effects.

Within each of these categories, there is a wide range of variables that can be considered for any structure. Details of these variables are 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 References [5], [2] and [6]. The variables driving the responses of individual building occupants in emergency situations are extremely 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 References [5], [6], [15] and [17].

Quantitative data for phases of behaviour, particularly warning and pre-travel activity times, can be obtained by observations of fire-safety management and occupant behaviour during fire incidents and monitored evacuations. These can then be combined with travel-time calculations to provide estimates of escape and evacuation times.

Although all the occupant and building characteristics features set out in Annex C can affect RSET times, the most important drivers are the following:

a) for occupants:

- number and distribution,
- alert/asleep,
- familiar and trained or unfamiliar,
- physical ability;

b) for buildings and building systems:

- warning system,
- fire-safety management and staff/occupant training,
- single or multiple enclosures and spatial complexity;

c) for fire scenarios:

- fire alarms and cues available to occupants,
- features of the fire and fire effluent.

Guidance on the choice and application of behavioural scenarios is provided in Annex D.

7 Estimation of pre-travel activity times

While detection and alarm times may be represented by single numbers, for pre-travel activity and travel times, each building occupant has his/her own individual time; see References [5] and [6]. It is, therefore, necessary to consider the pre-travel activity and travel time distributions of groups of occupants, firstly within individual occupied enclosures and then throughout the building and escape routes. Within each occupied enclosure, there are interactions between the distributions of pre-travel activity and travel times for occupant groups, so that the terms cannot be considered directly additive.

Guidance on the derivation of pre-travel activity times and on default pre-travel activity times from published data is provided in Annex E. An example of methods for the determination of evacuation start times used in Japan is provided in Annex F.

8 Estimation of travel times

Two important aspects of travel times are travel times to a protected escape route from each individual occupied enclosure and travel times though escape routes to the outside of a building for multi-storey or multi-enclosure buildings.

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

- distance of an occupant from the exit of choice (or the average travel distance to the exits for a group of occupants) and their walking speeds;
- time spent queuing (if any) at the exit, which in turn depends upon the occupant numbers using the exits, the maximum occupant flow capacity of the exit and the arrival time of each individual at the exit.

The distance it is necessary for each occupant to travel to a protected exit, and the average distance for a group of occupants, depends on the position of the occupant(s) within the enclosure, the size and shape of the enclosure, the distribution of available exits and the exit choice behaviour of the occupant(s). 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 an exit becomes contaminated by fire effluent or blocked by fire, it can be necessary to calculate evacuation times using the remaining available exits. It can be necessary for the travel distances to reflect the effect of the internal layout of a building rather than the direct distance for an empty building shell.

For individual occupants, time aspects such as physical capability (see Annex G), or time spent in way-finding 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.

These aspects and implications for evacuation of occupant populations are considered in Clauses 9 and 10.

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 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. Guidance on queue formation and exit flow capacity is provided in Annex H.

Guidance on effects of smoke density on travel speed is provided in Annex I.

9 Interactions between pre-travel activity time, walking time and exit flow time

Since pre-travel activity time for a group of occupants in an enclosure follows a distribution, there is a considerable degree of interaction between pre-travel activity times, walking times and exit flow times. For a detailed analysis of evacuation time, it is necessary to consider the location of each individual occupant, his/her individual pre-travel activity 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 computer evacuation simulation methods such as GridFlow [16], Simulex [12], CRISP2 [18] or EXODUS [19]. In practice, it can often be possible to reduce such complex interactions to simple calculations without incurring a significant error (see References [14] and [20]), providing the key parameters affecting outcomes are identified and adequately considered.

For sparsely occupied enclosures, 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 PTAT of the last few occupants to leave and their walking time to the exits. Since the flow capacity of the exits is not exceeded, queuing is unlikely to occur at the exits.

For densely occupied enclosures, the main drivers of evacuation time are the PTAT 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.

Guidance on simple calculation methods and a worked example from a computer simulation of an evacuation case showing the interactions between pre-travel activity times, walking times and exit flow time and their influence on evacuation time is shown in Annex H.

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

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 stairwell, then the time to evacuate depends on the flow capacity of the escape route and the ways 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 carried out using computer simulation models. The flow rate of occupants from individual enclosures depends upon the nature of the merging flows at the landings of the escape stairs with occupants already descending the stairs and on the flow capacity of the stairs.

As with single exposures, 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 PTAT distribution is very wide, such as is likely to be the case in sleeping accommodation at night, then it is unlikely to exceed the flow capacity of the escape routes and the evacuation time depends on the PTAT 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 PTAT of the first occupants to enter the stairs plus the flow time into and down the stairs. In experimental and modelling studies (see Reference [14]), the travel time to clear each floor of multi-storey buildings into a protected stairwell has been found to be heavily dependent on three parameters:

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

Where several sets of 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 the SFPE Handbook [11] (see Annex G). The standing area on a stair depends on the building design. Little guidance is available regarding occupant densities on stairs, but the densities obtained in these experiments was found to be quite low, approximately two persons per square metre, under crowded conditions with slow flows; see Reference [14].

Merge ratio data are sparse and there are three main assumptions that are often used.

- The flow is dominated by occupants on the stairs and the building empties from the top floor down.
- Occupants on the stairs “defer” to occupants at storey exits and the building empties from the bottom up.
- The merge ratio is around 50:50 at storey exits and the building empties from the bottom up.

Merging behaviour can have a considerable influence on the pattern of evacuation from a tall building. If the flow from the upper floor merges equally with the flow from the floor below, the flow rate from each floor is half the maximum flow rate from each storey exit, 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 Nelson and Mowrer’s chapter in the SFPE Handbook [11]. 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 stairs and 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 Reference [10]. 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 Reference [14].

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

Another consideration with regard to structural design requirements 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 stairwell, 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 dynamics of interactions between PTAT distributions on different floors and patterns of congestion and flows on stairs can vary when wide variations occur in warning and PTAT times and distributions on different floors of tall buildings. It can be necessary to consider the effects on evacuation via protected stairs resulting from fire development, such as contamination by fire effluent, fire penetration or structural damage in relation to the fire simulation dynamics.

11 Effects of fire effluent and heat on ASET and RSET

11.1 General

11.1.1 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

  — the fire-growth curve in terms of the mass loss rate, expressed in kilograms per second, of the fuel and the volume, expressed in kilograms per cubic metre, into which it is dispersed with time, and

  — the yield of toxic products, smoke and heat in the fire, for example kilograms of CO per kilogram of material burned.

  Guidance on calculation methods for these terms is given in ISO/TR 13387-1, ISO/TR 13387-2, ISO/TR 13387-3, ISO/TR 13387-4, ISO/TR 13387-5, ISO 16734 and ISO 16737.

b) the toxic or physiological potency of the heat and effluent, the exposure concentration, expressed in kilograms per cubic metre, or exposure dose, expressed in kilograms per cubic metre per minute, required to cause toxic effects and the equivalent effects of heat and smoke obscuration, which 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.

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 smoke, heat or toxic effluent.

11.1.2 The psychological and physiological effects of exposure to toxic smoke 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

- effects of seeing smoke or flames including
  - fear of approaching smoke or heat-logged areas or escape routes,
  - fear of fire or smoke in an occupied compartment. This may act as a stimulus to escape or a barrier to escape, depending upon the location and intensity of the fire or smoke, and
  - attraction towards fire in an occupied compartment (friendly fire syndrome) to observe or tackle fire;
- impaired vision resulting from the optical opacity of smoke and from the painful effects of irritant smoke products and heat on the eyes;
- respiratory tract pain and breathing difficulties or even respiratory tract injury, resulting from the inhalation of irritant smoke, which can be very hot. 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 subjects). Lung inflammation can also occur, usually after some hours, which can also lead to varying degrees of respiratory distress;
- asphyxiation from the inhalation of toxic gases, resulting in confusion and loss of consciousness (particularly in sensitive subjects such as the elderly and those with heart disease);
- 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 the first and second can be fatal if the degree of exposure is sufficient.

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

- psychological effects of seeing fire effluents on escape behaviour in the absence of direct exposure;
- psychological and physiological effects of exposure to heat and toxic smoke on escape behaviour and ability;
- point where exposure results in incapacitation;
- 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 relative safety or to use a particular escape route, and to determine the likely effects of any exposure sustained on escape capability and subsequent health. In some situations, it can also be necessary to consider tenability relative to possible physical hazards, such as structural failure affecting availability or passage through escape routes or threatening direct physical injury or death.

11.2 Simple criteria based upon zero exposure

Where a design fire calculation is based upon a descending upper layer of hot smoke filling an enclosure or escape route, and particularly where active smoke extraction is present, 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 willing and able to escape in clear air under such a layer and the downward heat radiation is considered tolerable. This represents a tenability criterion involving zero exposure to toxic effluent and exposure to radiant heat below a level of 2,5 kW/m^2.

11.3 Willingness to enter smoke

In situations where smoke is mixed down to near floor level, some building occupants are willing to move through dense smoke in some situations, but in other situations people might not be willing to enter smoke-logged escape routes, or might turn back or be unable to find an exit. Where heat is not an issue, the immediate effects of smoke depends on the visibility distance and the sensory irritancy of the smoke when people are exposed directly.

In a number of studies of fires in buildings, it was found that a proportion of people (approximately 30 %) turned back rather than continue through smoke-logged areas; see References [7], [22] and [23]. The average density at which people turned back was at a "visibility" distance of 3 m. The optical density, ρ_{OD}, expressed in units of "per metre", was 0,33 (extinction coefficient, 0,76) and women were more likely to turn back than men. A difficulty with this kind of statistic is that, in many fires in buildings, there is a choice between passing through smoke to an exit or turning back to take refuge in a place of relative safety such as a closed room. In some situations, people have moved through very dense smoke when the fire was behind them, while in other cases people have failed to move at all.

Behaviour can also depend on whether layering allows occupants to crouch down to levels where the smoke density is lower and whether low-level lighting is used to improve visibility.

As an approximate guide, it can be assumed that occupants will not use an escape route if the visibility in that route is less than 3 m (ρ_{OD} = 0,33 m^{-1}; extinction coefficient, 0,76). However, if they enter an escape route contaminated to this optical density and become exposed to the smoke, then their ability to progress depends on both the optical density and the irritancy of the smoke (see 11.4 and 11.5).

11.4 Ability to move through smoke

Ability to escape through smoke depends on the effects of irritancy and visual obscuration, on the ability to move through building spaces and on the ability to locate escape routes and exits. More stringent criteria are suggested for large building enclosures than for domestic enclosures, since it can be necessary for occupants to see for greater distances to locate exits and they are more likely to be unfamiliar with their surroundings.

Criteria for choosing design limits are discussed in ISO 13571:2007, in Annex I, in the SFPE Handbook, Chapters 2 to 6 [24] and in Reference [17]. Effects of smoke density and irritancy on walking speed are considered in 11.5.

11.5 Effects of smoke on walking speed

Exposure to smoke affects RSET calculations because walking speed has been found to be related to smoke density and irritancy; see References [6], [25] and [26]. Simple expressions for the relationships between unrestricted walking speed and smoke density for irritant and non-irritant smoke are shown in Annex I.

11.6 Effects of visibility or exposure to fire and heat

With regard to flames, an important criterion is the visual appearance of fire to occupants (flame area and height) and its position relative to occupant location and potential escape routes. For example, it can be considered that occupants are likely to move away from a location where the width or height of the flames (view angle) is more than a critical figure, or that they are unlikely to enter an escape route containing a flaming fire.

Exposure to radiant heat can occur when it is necessary for occupants to pass close to a fire or under a hot effluent layer. Combined exposure to radiant and convected heat can occur when occupants are exposed directly to hot air or effluent.

Tenability limits for skin exposure to radiant heat or convected heat have been proposed as an exposure resulting in severe pain to unprotected skin; see Reference [24].

Expressions for the calculation of tenability times for the effects of convected and radiant heat are given in ISO 13571 and the SFPE Handbook, Chapters 2 to 6 [24].

11.7 Effects of exposure to toxic gases

Toxic gases in fires consist of a mixture of irritants and asphyxiants. Irritants affect escape efficiency and movement speed at low concentrations due to the painful and debilitating effects on the eyes and the pain and breathing difficulties resulting from effects on the nose, mouth, throat and lungs. At high concentrations, they can cause incapacitation. The effects depend upon the concentrations of the mixed irritants present and the potency of each irritant species.

Irritants in fire effluent consist of a range of organic compounds, including acrolein and formaldehyde, which are likely to be present in any fire effluent atmosphere at concentrations that vary depending upon the chemical composition of the fuel and the fire decomposition conditions. Other irritant species that can be present are acid gases such as hydrogen chloride or nitrogen oxides. The presence of these irritants depends upon the appropriate chemical elements being present in the fuel; see References [24].

Calculation methods for assessing tenability limits for irritants for ASET calculations are given in ISO 13571. Effects of exposure to irritant smoke on movement speed for RSET calculations are give in Annex I and References [6] and [27].

Asphyxiant gases important with respect to incapacitation and death in fires are carbon monoxide, hydrogen cyanide, carbon dioxide and low oxygen. Asphyxiant gases have little or no immediate effect on exposed subjects, but when a sufficient exposure dose has been inhaled during the course of a fire, confusion, rapidly followed by incapacitation, occurs due to collapse and loss of consciousness. If the subject is not rescued when incapacitation occurs, death is likely within a few minutes.

For these reasons, asphyxiant gases can be considered as having no significant effect on evacuation behaviour or movement speed (RSET) at the early stages of exposure, but are a major determinant of the ASET endpoint: the time when incapacitation is predicted. Calculation methods for tenability endpoints for asphyxiant gases are given in ISO 13571.

Annex A
(informative)

Guidance on the evaluation of detection and warning times

A.1 General

Detection and the provision of warnings often involve automatic systems but can also rely to some extent on the behaviour of occupants; see Reference [6].

The simplest situation exists when an automatic detection system is in place that sounds a general alarm to all occupants when any one detector is triggered. In this situation, the evacuation time for all occupants starts simultaneously when the alarm is triggered. Time to alarm is basically the same as time to detection. Time to detection depends upon fire growth and effluent movement, which are described in ISO/TR 13387-2 and ISO/TR 13387-5.

A more complex situation arises when there is no automatic detection and alarm system and only a single alarm is triggered in one part of a building or when a pre-alarm system is in place. In these cases, the initial detection provides a cue or an alarm only to the first occupants to discover the fire or to the building security and not to all occupants. If the fire is discovered by an occupant becoming aware of the fire cues, such as smoke or noise from a local detector/alarm, this also represents the time to awareness of the first occupant. If the fire is detected automatically in a two-stage system, this is followed immediately by a pre-alarm, which alerts the first occupant (usually security). In all three situations, there is a variable time delay following the time when the first person becomes alerted; see References [28] and [29].

The next phase involves the behaviour of the first occupants alerted, during which they recognize the situation and respond by behaving in a range of ways, such as investigating the fire and raising a general alarm or warning. Once the general alarm is raised, the remainder of the building occupants (or occupants of the enclosures first affected by the fire) are made aware of the fire and enter the pre-travel activity phase of their evacuation.

There are thus three basic detection and alarm scenarios:

a) automatic detection throughout the building, activating an immediate general alarm to occupants of all affected parts of the building; t_{warn} is effectively zero;

b) automatic detection throughout the building providing a pre-alarm to management or security, with a manually activated general warning system sounding throughout affected occupied areas and a general alarm sounding after a fixed delay if the pre-alarm is not cancelled; t_{warn} is taken as the time-out delay (usually 2 min to 5 min).

   Where there is no fixed time delay, or where security can cancel the pre-alarm, then it can be important to estimate the time likely required for security to investigate and sound a general warning, if necessary.

   If a voice alarm system is used for either an A.1 or A.2 system (see D.3.2), it can be necessary to add the time taken for the message to be spoken twice, to the alarm time;

c) 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; t_{warn} depends upon the behavioural scenario and behaviour of the first occupant(s) alerted.

   Warning times can be short (less than approximately 2 min) if the person alerted is well-trained, otherwise they can be long and unpredictable.

A.2 Effect of evacuation strategy on warning time

A further important variable affecting warning time, particularly for large buildings consisting of more than one fire compartment, is the warning management strategy.

For smaller or uncompartmented buildings, a simultaneous evacuation alarm can be provided to all occupants irrespective of their location within the building relative to the point of fire origin.

For buildings consisting of a number of compartments (usually multi-storey buildings), a phased evacuation strategy can be used. Occupants of compartments affected by the fire are instructed to evacuate first. Occupants on other floors or compartments are instructed to stand by for further instructions and to evacuate only if and when considered necessary as a result of further fire spread. In such situations, the time from ignition to evacuation alarm can be up to 1 h or more. For some buildings, a defend-in-place strategy can be used, so that only immediately affected parts of the building are evacuated. For such buildings, the time required for protection is long and indefinite, so it is necessary that the compartment be able to contain the fire until the fuel load is burned out.

Annex B
(informative)

Pre-travel activity behaviours and determinants

B.1 Two components of pre-travel activity time

The two components of pre-travel activity time (recognition and response) have the characteristics given in Clause B.2 and Clause B.3, respectively.

B.2 Recognition

This consists of a period after an alarm or cue is evident but before occupants of a building begin to respond.

During the recognition period, occupants can continue with the activities engaged in before the alarm cue, such as working, shopping or sitting. The length of the recognition period can be extremely variable, depending upon factors such as the type of building, the occupant characteristics and the building alarm and management system; see References [4], [5], [6], [9] and [30].

In single-enclosure buildings that are well managed, the recognition period is likely to be short (between a few seconds and 1 min to 2 min). In multi-enclosure buildings where occupants can be remote from the fire (especially those where occupants can be sleeping, such as hotels, residential homes and hostels), the recognition times can vary considerably between a few minutes and up to 1 h or more; see References [4], [5] and [6]. The recognition time ends when the occupants have accepted that it is necessary to respond.

During the recognition process, each occupant is engaged in his/her normal activities, but is receiving and processing cues about the developing emergency situation. For each individual, this process ends when he/she decides to take some action in response to the emergency cues received.

B.3 Response

This consists of a period after occupants recognize the alarms or cues and begin to respond to them, but before they begin the travel phase of evacuation (where this is necessary). As with the recognition period, this can range from a few seconds to many minutes, depending upon the circumstances; see References [5], [6] and [31].

During the response process, occupants cease their normal activities and engage in a variety of activities related to the developing emergency. At the end of the response process, each occupant has decided either to remain in the same enclosure, to move to another, safer, location or to begin evacuation.

Examples of activities undertaken during the response time include

— investigative behaviour, including action to determine the source, reality or importance of a fire alarm or cue;

— stopping machinery/production processes or securing/protecting money and other assets;

— seeking and gathering together children and other family members;

— fighting the fire;

— determining the appropriate exit route (i.e. "way-finding");

— other activities not fully contributing to effective evacuation where necessary (e.g. acting on incorrect or misleading information);

— alerting others.

B.4 Total pre-travel activity times

Pre-travel activity times can vary considerably for different individuals or groups of individuals both within an enclosure and in different enclosures within the same building. The distribution of pre-travel activity times depends upon a range of factors, including the occupant characteristics, their proximity to and knowledge of the fire as afforded by the architecture of the setting, the warning system and management systems.

For example, in an open-plan setting such as a theatre auditorium, the distribution of pre-travel activity times is likely to be narrow (everyone starting to move at about the same time). In a multi-enclosure setting, such as a hotel, there is likely to be a wide distribution of pre-travel activity times. Those in the enclosure of fire origin can complete the pre-travel activity process before those in other enclosures even become aware of the fire.

The provision of reliable data on the pre-travel activity times expected in various situations and their incorporation into egress behaviour models is an important requirement for the assessment of escape time, and, therefore, for fire-safety engineering design. Although currently available databases of pre-travel activity times are somewhat limited, they do provide a basis for design calculations appropriate to a range of occupancy types; see References [5], [9], [4] and [17]. Guidance on default values is given in Annex E.

A range of factors can be taken into account in order to estimate pre-travel activity time. The principal ones are as follows:

a) building parameters:

   1) occupancy use,

   2) floor plans, layout and dimensions,

   3) contents,

   4) warning system,

   5) fire safety management emergency procedures;

b) occupant status:

   1) occupant numbers and location,

   2) occupant characteristics, such as age and health status,

   3) occupant activities,

   4) occupant condition;

c) fire simulation dynamics:

   1) building condition and fire location,

   2) visibility of smoke or fire,

   3) exposure to fire effluent or heat,

   4) fire alarm status and type,

   5) other warnings or cues (e.g. from management or other occupants),

   6) active protection status.

Annex C
(informative)

Detailed information needed for RSET calculations

C.1 General

In order to evaluate RSET, detailed input information is required in four main areas:

- building design and emergency life-safety management strategy;
- occupant characteristics;
- fire simulation dynamics;
- effects of intervention.

The response of occupants to a fire condition is influenced by a whole 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, behaviour 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 (fire brigade and rescue facilities). These aspects are described in more detail in C.2 to C.5.

C.2 Building characteristics and fire safety management strategy

Some of the major elements of the life safety evaluation processes include details of the building characteristics, its management in relation to fire safety and the emergency life-safety strategy. These comprise the basic building dimensions, internal arrangement and services relevant to fire safety, which are as follows:

- layout and geometry (including size, building height, ceiling height, layout, complexity, compartmentation, subdivision into internal spaces, interconnection of spaces, travel distances, door and stair corridor widths, normal circulation routes, opening/closing forces of fire doors, door furniture);
- escape routes [including visual access, complexity, protection (passive/active), lengths, horizontal, vertical (escape upwards or downwards), accessibility (e.g. by break-glass and key only, by crash bar), use during normal flows in building, final exits (number and distribution related to characterization data)];
- functions/uses in particular locations within the building that can impact on likely behavioural responses and escape-route usage (some functions may tend to provide easy access and escape while others may not);
- fire-safety management system (including management of the building, management and maintenance of essential equipment, management of staff and occupants of the building, fire prevention management, management flexibility, training of staff and training of occupants, security and fire surveillance, emergency procedures);
- life-safety strategy (including life-safety design philosophy, evacuation strategies, passive/active fire control systems, fire detection, alarm and communication systems, facilities for the fire brigade, emergency lighting, way-finding systems, fire safety management);

- application of active systems (including sprinkler/spray systems, sprinklers for life-safety, gas suppression systems, smoke management or extraction and ventilation systems);
- signage and lighting (including emergency lighting);
- refuge areas (form, degrees of protection and tolerability, communication systems and connection to escape routes, staging areas, access for assisted escape or rescue);
- environmental considerations (e.g. wind and internal air pressurization on door opening force, evacuations in wet, hot or cold conditions, dress requirements, effect of snow on exits, daylight vs night time).

C.3 Occupant characteristics

Another major element of the life-safety evaluation process is the occupant characteristics. The main considerations are the likely nature and timing of occupant response to cues or alarms and the likely subsequent pattern and timing of occupant movements, particularly in carrying out an evacuation, if required. Also important is the likely susceptibility of the occupants to the sight of or exposure to fire effluent or heat.

Occupant characteristics for consideration include

- population numbers and density: expected numbers in each occupied space including time and seasonal variations;
- familiarity with the building: depends on factors such as occupancy type, frequency of visits and participation in emergency evacuations;
- distribution and activities;
- activity affiliation: occupant's bond/commitment to the activity;
- alertness: depends on factors such as activities, time of day, asleep or awake;
- mobility: depends on factors such as age, temporary limitation, health conditions and any physical disability;
- sensory impairments, mental ability and perceptual limitations, such as hearing or visual impairments;
- social affiliation: extent to which occupants represent individuals or groups, such as family groups, groups of friends, etc.;
- object affiliation, etc.;
- role and responsibility: includes categories such as member of the public, manager, floor warden, etc.;
- location: location in building relative to escape routes, etc.;
- commitment: extent of commitment to activities engaged in before the fire;
- focal point: point where occupant's attention is directed, such as the stage in a theatre or a counter in a shop;
- responsiveness: extent to which occupant is likely to respond to alarms, etc.;
- changes in occupant condition throughout the course of the evacuation, as determined by exposure to effects of fire.

C.4 Fire simulation dynamics

A third major element of the life-safety evaluation process is the fire simulation dynamics. The object of the life-safety design is to protect occupants from exposure to fire effluents or heat (or physical trauma from structural failure). This is achieved by a combination of the provision of adequate means of escape and protection of occupied spaces. In order to evaluate the life safety of persons during a fire, it is necessary to obtain continuous information on the extent of the fire and fire effluent and their effect on the building.

It is necessary to consider the following specific factors:

a) Fire alarms and cues available to occupants: When the fire originates in an occupied enclosure, it is necessary to determine the “visibility of the flames and smoke”, so that an estimate can be made of the time when occupants become aware of the situation and how they are likely to respond to it. For both occupied and unoccupied fire enclosures, it is necessary to know when an automatic alarm system would be triggered, and when information on fire spread would be available from analogue addressable systems. The main requirement is to be able to determine what information is available to building occupants throughout the fire incident.

b) Fire size and extent, smoke density, toxic gas concentrations, temperature and heat flux in all building enclosures: For all enclosures in the building, it is necessary to know the size of the fire, the extent to which it is contained or has spread through adjacent enclosures, any structural failures and the temperature and heat fluxes in affected enclosures. It is also necessary to know the optical density and concentrations of irritant gases in the smoke, and the concentrations of asphyxiant gases present. For occupied enclosures, this information is required to assess the tenability of the enclosure for occupants, and the extent to which their escape out of each enclosure is affected. For unoccupied enclosures, the information is required particularly if they form part of potential escape routes or refuges. Where the fire effluent is in well-defined layers, the height of the hot layer and downward radiant flux may be reported.

c) Activation of suppression and smoke-control systems: The activation of suppression and smoke-control systems impacts the spread of fire effluent throughout the built environment, which determines what, if any, effluent occupants will encounter during their evacuation or refuge.

C.5 Intervention effects

Circumstances can arise in a building where the intervention of the fire brigade is necessary to secure the safety of the occupants. To assist the fire brigade in the execution of intervention strategies, it is necessary to include appropriate facilities in the design of the building. This is considered beyond the scope of this Technical Report.

NOTE The use of lifts (elevators) in emergency evacuations is not dealt with in this Technical Report. For guidance concerning lifts, the reader is referred to ISO/TR 25743, ISO/TR 16765, EN 81-72 and EN 81-73.

Annex D
(informative)

Design behavioural scenarios for derivation of default RSET variables

D.1 General

For the method described in this Annex, a set of key qualitative features of occupant behaviour is used to specify a small number of basic design behavioural scenarios; see Reference [17]. The main scenario categorizations are based upon whether the occupants are familiar or unfamiliar with the building and systems and whether they are awake or asleep, although each scenario also involves a set of additional typical features.

For each scenario category, factors affecting both occupant behaviour and the time required for carrying out various activities during different phases of an evacuation are described. Default alarm times and pre-travel activity time distributions are derived depending mainly upon the fire-safety management strategies and the warning system in place. Certain building characteristics are also considered important, particularly spatial complexity, travel distances, occupancy factors, exits and escape routes. These mainly affect travel times and, in some situations, pre-travel activity times. The basic scenarios may be further subdivided into more closely defined scenarios in each class.

As described in Clause 6, in order to evaluate RSET times for any specific occupied structure it is necessary to develop a design behavioural scenario. For any specific design of an occupied structure, it can be necessary to consider all aspects of the variables 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 References [2], [5] and [7]. 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 References [6], [5] and [15].

Quantitative data for phases of behaviour, particularly warning and pre-travel activity 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 References [5], [4] and [17]. 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 D.1. For each, the default time can be derived for alarm and pre-travel activity times, depending mainly upon the three safety-management strategies and warning system in place.

Certain building characteristics are also important, particularly spatial complexity, travel distances, occupancy factors, exits and escape routes. These mainly affect travel times and, in some situations, pre-travel activity times. The basic scenarios may be further subdivided into more closely defined scenarios in each class. Although all the occupant and building characteristics can affect escape times, the most important drivers are the following:

a) for occupants:

— number and distribution,

— alert/asleep,

— familiar and trained or unfamiliar,

— physical ability;

b) for buildings and building systems:

— warning system,

— fire-safety management and staff/occupant training,

— single or multiple enclosures and spatial complexity;

c) for fire scenarios:

— fire alarms and cues available to occupants,

— features of the fire and fire effluent.

For each scenario category shown in Table D.1, factors affecting both occupant behaviour and the time required for carrying out various activities during different phases of an evacuation are described. See Annex F for further details.

Table D.1 — Design behavioural scenarios and occupancy types

Category	Occupant alertness	Occupant familiarity	Occupant density	Enclosures/ complexity	Examples of occupancy types
A	Awake	Familiar	Low	One or many	Office or workshop areas
B1	Awake	Unfamiliar	High	One or few	Shop, restaurant, circulation space, bar
B2	Awake	Unfamiliar	High	One with focal point	Cinema or theatre auditorium
C	Asleep				Dwelling bedroom
Ci	Individual occupancy	Familiar	Low	Few	Without 24 h on-site management
Cii	Managed occupancy	—	—	—	Bedroom in serviced flats, halls of residence, residence, etc.
Ciii	Asleep	Unfamiliar	Low	Many	Hotel, hostel bedroom
D	Medical care	Unfamiliar	Low	Many	Residential (institutional)
E	Transportation	Unfamiliar	High	Many	Railway station/airport halls

From the observations made, it is considered that each basic category has certain general requirements and ranges of likely warning and pre-travel activity times. 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 is shown.

Any particular building can contain a number of enclosures in different design behavioural scenario categories. For example, a hotel is likely to included 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 can also be different scenarios at different times of day. Thus, it can be considered that a hotel bedroom during the day fits more into category B2 than Ciii. it is necessary, therefore, to consider all of these scenarios.

It is also possible to define more specific sub-scenarios within each category. The main consideration is that the scenario is defined in terms of the behavioural characteristics and that data are obtained for behavioural response timed for the defined scenario that can be used to inform the design of future occupancies with similar characteristics.

These basic behavioural scenarios are mainly intended for the estimation of initial pre-travel activity times for occupants in response 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. In situations where the occupants are in the fire enclosure or become exposed to fire effluent before entering their travel phase, then it can also be necessary to consider the effects on behaviour of seeing fire or smoke. These can reduce or increase pre-travel activity times, depending upon the situation; see References [5], [31] and Annex F.

D.2 Features of design behavioural scenario categories

D.2.1 Category A — Occupants awake and familiar

EXAMPLES Working space: office or workshop, warehouse.

Scenario features are as follows.

— Occupants are awake and engaged and are familiar with the building and its systems. They visit the building frequently and spend a significant amount of time there, usually in a working capacity.

— Occupants can be present in small groups in a single enclosure or dispersed in small numbers throughout a number of enclosures, usually with low occupant densities. Pre-travel activity time can be lengthened somewhat when occupants are dispersed.

— Occupants are involved in a variety of individual or small-group activities, they are awake and familiar with the building features, including alarm systems and fire safety management procedures.

— Occupants have well-defined roles and carry some responsibility for the building, its operation and emergency strategies and are trained in emergency procedures.

— Floor wardens and other staff have special responsibilities to ensure a rapid and efficient evacuation if alarms sound. Occupants are staff and can expect disciplinary action if they fail to follow emergency procedures and evacuate in an efficient manner.

In well-managed office buildings, with good management procedures and well-trained staff, pre-travel activity times should be very short, even with a sounder alarm system. Particularly in a multi-enclosure system, an important consideration is the pre-travel activity time of the occupants slowest to respond, especially isolated individuals. Travel times depend mainly on travel distance, unless occupant densities are high, when queuing at exits can occur and flow times can dominate. Poor fire-safety management can lead to long pre-travel activity times. Office buildings are most likely to fit into building levels B1 or B2 (see D.3.3), and since occupants are familiar with the building, spatial complexity should be less important unless outside visitors are commonly present. Reported pre-travel activity times from offices during well-managed evacuations tend to be very short, between a few seconds and a few minutes (see References [5] and [6]) and times for occupants to reach a safe escape route are rarely more than a few minutes from general alarm; see References [5].

D.2.2 Category B — Occupants awake and unfamiliar

EXAMPLES

a) No focal point: shopping enclosure, restaurant, bar, supermarket, department store floor, mall area, airport check in or lounge areas, circulation space, restaurant, day centre;

b) Focal point: assembly, cinema, theatre.

Scenario features are as follows.

— Occupants are awake and active but largely unfamiliar with the building and systems, they are committed to various activities, family and friends and might not respond to alarms. They might not have ever visited the building before.

— Authority figures (sales staff, managers, stewards) are present who are trained in the building emergency management systems and procedures.

— A rapid sweep of the area by staff can be used to ensure a rapid customer evacuation, otherwise alarms might not trigger an evacuation, although voice alarms or personal address messages can be effective.

— Special provisions can be necessary for restaurant areas or bars.

— Sports stadia or very large arenas can be considered a special subset.

— Layout of assembly enclosures and exits should be simple but subsequent escape routes can be complex and hard to identify quickly.

Sales areas can be large with complex layouts and visibility limited by stock. Restaurant areas can also be present. There is also likely to be a wider range of physical and mental abilities (including children, the elderly and family groups who are scattered at the time of the emergency). Customers can be reluctant to leave goods they have collected or paid for (e.g. in supermarkets). In theatres, occupants are attending to the stage or screen, but this provides a focal point that can be used by management to control an evacuation. Staff training is, therefore, particularly important in interrupting the ongoing activity swiftly and provides an opportunity to impose rapid control.

During a number of monitored evacuations and incident investigations (see References [5]), pre-travel activity times have been short, with narrow distributions, when management was efficient and staff acted quickly to encourage occupants to evacuate. In a least one occasion when staff did not act quickly, much longer pre-travel activity times occurred; see References [5]. When design occupant densities are high, evacuation times are mainly dependent on exit flow capacity, especially if exit choice is not optimal (as is often the case); see References [16].

D.2.3 Category C — Sleeping

EXAMPLES

a) Familiar: apartment block, house, residential home;

b) Unfamiliar: hotel, hostel.

Scenario features are as follows.

— Low occupant densities and mixed ability and age of residents, who can be sleeping.

— For residences, occupants should be familiar with warning and evacuation procedures. Fire-safety management is often basic in residences but can be more developed in managed accommodation.

— Dwellings are small, with simple layouts and are familiar to occupants.

— When one member of a household detects a fire cue or alarm his/her first action is usually to investigate, but warning others is often a high priority, so that once detection has occurred, warnings to other occupants can be delivered within a short time.

— Pre-travel activity times can be long, especially with sleeping occupants or when cues are ambiguous or occupants inebriated.

— For hotels and hostels, occupants are largely unfamiliar with the building and systems and they are dispersed among a large number of enclosures. Some authority figures, consisting of staff, security and managers who are trained in the building emergency systems and emergency management procedures, may be present.

— Non-staff occupants can lack a sense of responsibility for the building and systems, and might not respond to alarms. Their main commitment is activities such as sleeping.

— Layout is likely complex and escape routes hard to identify quickly.

For these reasons, it is unlikely that a rapid and efficient evacuation will be achieved. If there is a sufficient number of well-trained staff present and if they act quickly, then a rapid sweep can be used to secure a local evacuation of an affected area. In many situations, evacuation can be counterproductive, since it is likely that occupants can be relatively safe in their rooms but can enter escape routes contaminated with fire effluent, especially if evacuating after a significant delay. Pre-travel activity times for even the first few occupants to respond can be very long (up to 1 h), and the distribution of pre-travel activity times is likely to be very wide. Evacuation times are likely to be dependent on maximum pre-travel activity times and walking times; flow restrictions at potential "pinch" points are unlikely to occur. Occupants can be reluctant to leave their belongings and the temporary refuge of their rooms. For these reasons, it can be necessary for passive fire protection to be used as a major strategy.

D.2.4 Category D — Medical care

EXAMPLES Hospitals and nursing homes.

Scenario features are as for category C with the addition of the following.

— Occupants can have low levels of physical and/or mental abilities to respond to emergencies.

— Each occupant can be expected to require assistance from one or more staff member to evacuate.

— A high level of management supervision and participation in emergency procedures is expected.

— Occupants can be bedridden and/or attached to medical appliances (e.g. drips, monitors).

— Evacuation involves moving beds and wheelchairs.

D.2.5 Category E — Transportation

D.2.5.1 Buildings — Special case of awake and unfamiliar

EXAMPLES Railway stations and airports.

Scenario features are as follows.

— There are many complex enclosures and very large spaces; escape routes are not easily identified.

— Security restrictions in some areas impose behavioural limitations on occupant responses.

— Occupants are likely encumbered by luggage, which they can be unwilling to abandon in an emergency situation.

— The occupant density is high.

— Occupants can be largely unfamiliar with the building and systems but authority figures, consisting of sales staff, security, managers and stewards who are trained in the building emergency systems and emergency management procedures, are present.

— Special provisions can be necessary for restaurant areas or bars.

— Occupants speak a variety of languages.

D.2.5.2 Vehicles

EXAMPLE Coaches, trains, ships.

The scenario features are that alarm times (time from detection to warning) are dependent on the detection and warning systems in use and the behaviour of the first occupants alerted (security staff or occupants discovering fires). Depending upon the system in use, they can be calculable or, particularly where they rely on human response, research data can be necessary.

D.3 Major behavioural modifiers in each scenario category

D.3.1 Levels

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

— quality of the alarm system (classified into levels A1 to A3; see D.3.2);

— complexity of the building (classified into levels B1 to B3; see D.3.3);

— quality of the fire safety management, in particular (classified into levels M1 to M3; see D.3.4).

D.3.2 Effect of alarm system on pre-travel activity

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

— alarm system level A1: automatic detection throughout the building, activating an immediate general alarm to occupants of all affected parts of the building;

— alarm system level A2 (two-stage): automatic detection throughout the building providing a pre-alarm to management or security, with a manually activated general warning system sounding throughout affected occupied areas and a general alarm after a fixed delay if the pre-alarm is not cancelled;

— alarm system level A3: 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.

D.3.3 Effect of building complexity on evacuation time to a protected escape route

Building complexity affects pre-travel activity time and time required for way-finding (searching for a suitable escape route) as follows:

— building level B1 (e.g. simple supermarket): 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;

— building level B2 (e.g. simple, multi-storey office block): simple multi-enclosure, usually multi-storey, building, with most features prescriptively designed and simple internal layouts;

— building level B3: large complex building. This includes large building complexes with the integration of a number of existing buildings on the same site, common with old hotels or department stores, aswell as with large modern complexes, such as leisure centres, shopping centres and airports. The important feature is that the internal layout and enclosures involve often large and complex spaces so that occupants can be presented with way-finding difficulties during an evacuation and the management of an evacuation, therefore, presents particular challenges.

D.3.4 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 activity time), and the subsequent conduct of the travel phase, has been found to be very dependent on the implementation of the fire-safety management strategy. This depends on elements such as staff training and emergency management practice, but is also dependent on the quality of the tools at the disposal of the 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:

- management level M1: the normal occupants (staff or residents) are 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 is a high ratio of trained staff to visitors. The system and procedures are subject to independent certification, including a regular audit with monitored evacuations for which it is necessary that the performance match the assumed design performance. Security videotapes from any incidents or unwanted alarms are made available for audit under the certification scheme. This level also usually implies 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 used by the public, it can be necessary to provide a voice alarm system;

- management level M2: this is similar to level M1, but with a lower staff ratio and floor wardens might not always be present. There might not be an 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;

- management level M3: this represents standard facilities with a basic, minimum fire-safety management. There is no independent audit. The building may be level B3 and alarm system level 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.

Further guidance on fire-safety management is provided in BS 5588-12 [32].

D.3.5 Estimation of pre-travel activity times based on design behavioural scenario

While detection and alarm times may be represented by single numbers, a difficulty with respect to pre-travel activity and travel times is that each building occupant has his/her own individual time; see References [5], [6] and [16]. It is, therefore, necessary to consider the pre-travel activity 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 among the distributions of pre-travel activity and travel times for occupant groups, so that the terms cannot be considered directly additive.

Pre-travel activity time distributions depend primarily upon the design behavioural scenario category and the fire-safety management level, with building complexity also having some influence. Computer simulations of building evacuations may consider the evacuation time and travel time for each individual occupant. However, it is possible to make an adequate estimation of evacuation times for most situations by considering two main criteria: the pre-travel activity times of the first few occupants in an enclosure to move (pre-travel activity time of the 1st percentile of occupants) and the pre-travel activity times of the last few occupants to move (99th percentile of occupants). Data on pre-travel activity time distributions for different behavioural scenarios are currently extremely limited, but some measured distributions exist; see References [5], [15], [4], [33], [34], [9], [35], [36], [37], [38], [39], [40], [41]. Based upon the limited data available, suggested default values for pre-travel activity time 1st and 99th percentiles for different design behavioural scenarios are presented in Annex E. The overall findings from the data are that both pre-travel activity times for 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 any building containing occupants who are sleeping.

Annex E
(informative)

Pre-travel activity time distribution data and derivations

E.1 General

Pre-travel activity time distributions depend primarily upon the behavioural scenario and the fire-safety management level, with building complexity also having some influence. Computer simulations of building evacuations may consider the evacuation time and travel time for each individual occupant. However, it is possible to make an adequate estimation of evacuation times for most situations by considering two main criteria: the pre-travel activity times of the first few occupants in an enclosure to move (pre-travel activity time of the 1st percentile of occupants) and the pre-travel activity times of the last few occupants to move (99th percentile of occupants). Data on pre-travel activity time distributions for different behavioural scenarios are currently extremely limited, but some measured distributions exist for a range of occupancies; see References [4], [5], [8], [14], [33], [34], [35], [36], [37], [38], [39], [40] and [41]. Some examples are provided here, and based upon the limited data available, suggested default values for pre-travel activity time 1st and 99th percentiles for different design behavioural scenarios are presented in Table C.2 of the UK Fire Engineering Code [17]. The overall findings from the data are that pre-travel activity 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 the warning system are of a lower standard, and in any building containing occupants who may be sleeping.

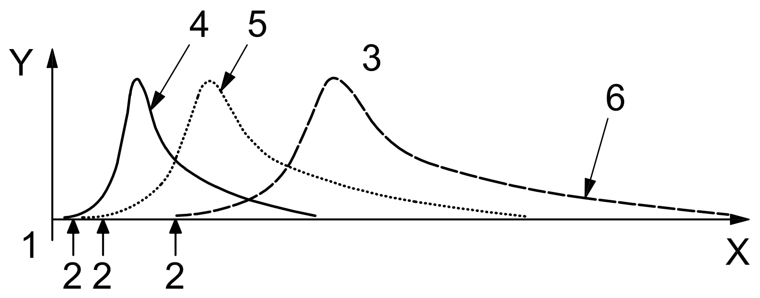
Pre-travel activity time data are available from a number of studies, two of which report data from a range of experiments in different occupancies; see References [5] and [4]. Pre-travel activity time is sometimes described as the “pre-movement time”, “delay time”, “initial response time”, or the “time to start”.

Pre-travel activity distributions consist of two phases:

— time from alarm to the movement of the first few occupants to begin their travel phase;

— subsequent distribution of times for the population of occupants to begin their travel phase.

Once the first few occupants begin to move, pre-travel activity distributions tend to follow approximately log-normal distributions, with a rapid increase in the number of occupants starting to move soon after the beginning of the distribution and a long queue until the last few occupants move, as illustrated in Figure E.1. The characteristics of the occupants, the quality of warnings and management affects both the time the first occupants begin to move and the width of the distribution.



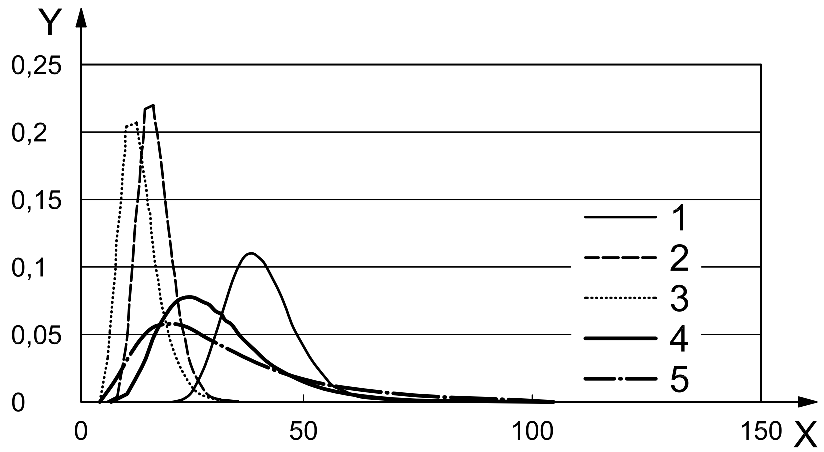
Key

X	time, expressed in seconds	3	$t_{pre(occupant\ distribution)}$
Y	persons per second	4	PTAT distribution – management level M1
1	alarm	5	PTAT distribution – management level M2
2	$t_{pre(first\ occupants)}$	6	PTAT distribution – management level M3

NOTE Pre-travel activity of first occupants to move and subsequent pre-travel activity time distribution is lengthened by progressively lower levels of fire-safety management.

Figure E.1 — Representation of pre-travel activity time distributions and effects of different levels of fire safety management

Figure E.2 illustrates pre-travel activity time distributions measured in a number of unannounced monitored evacuations. These include a restaurant in a shopping mall, two outpatient clinics in a hospital and three retail stores. The curves all show a similar shape, with short periods before travel begins and subsequent narrow distributions, all representing well-managed cases.



Key

X	time, expressed in seconds	3	Luton EC
Y	frequency	4	Sprucefield
1	Sarah's	5	Belfast
2	Luton WR1		

Figure E.2 — Some examples of measured pre-travel activity time distributions

It is important that realistic pre-travel activity time data be used in evacuation time calculations.

The most important considerations are the pre-travel activity times of the first few occupants in each affected enclosure (for example, the 1st percentile) and the pre-travel activity time of the last few occupants (for example, the 99th percentile). Pre-travel activity time data have been reported from video records of occupant behaviour in a small number of fire incidents and a significant number of unannounced evacuations in a range of occupancies; see References [4], [5], [8], [14], [33], [34], [35], [36], [37], [38], [39], [40] and [41]. It is also possible to estimate maximum pre-travel activity times from total building evacuation time data; see Reference [5].

The results of these studies have shown that pre-travel activity times are very dependent on occupant and building factors, expressed in terms of the design behavioural scenario, and for any particular scenario on the fire safety management. The type of warning system and the building complexity also have some influence; see References [5] and [6].

Data on delay times for office buildings, mid- and high-rise apartment buildings and retail stores have been published in several papers and reports; see References [5], [10], [15], [42], [37], [38], [33] and [34]. Studies have shown that delay times can vary according to the cue occupants receive (alarm bells, warnings by staff, voice announcements or smoke, for example); see References [9] and [38]. The series of evacuation drills in mid- and high-rise apartment buildings underway at the National Research Council of Canada has provided data on time-to-start in summer and winter; see References [10], [40] and [41]. Similar data are also available from studies undertaken in Australia. The retail store studies, as well as others, have demonstrated the effectiveness of staff training in reducing the delay time and speeding up an evacuation; see Reference [5]. Data on pre-travel activity delays have been collected in Japan. Data from five studies are summarized and reported in a recent paper; see Reference [4]. The paper includes results of overnight experiments conducted at a training facility. The subjects were at the training facility because they had fire-safety responsibilities in their positions at hotels and health-care facilities. An evacuation drill was held during the night and the subjects were videotaped as they left their rooms. Ninety percent of the subjects left their rooms within 90 s, but delays lasted as long as 5 min. This research study also looked at the relationship between initial response time and self-reported levels of intoxication, levels of sleep and time asleep. They did not find any marked effect. The researchers point out in the paper that those attending the training would recognize the need for immediate reaction on hearing an alarm and, coupled with the fact that this was a training drill, that the time durations would be considerably longer in an actual fire. The paper also summarizes the findings on mean evacuation delays in four actual fires. Two fires, for which the type of occupancy was not described, had mean delay times of 2,82 min and 3,68 min; for a hotel fire, they reported a mean delay time of 7,0 min; and for a fire in a multi-story condominium, they reported a mean delay time of 5 min to 10 min, derived from questionnaires.

As a result of the data collected from the incidents and studies described above, evacuation model developers and users should have a growing database of essential information. Data are available on delay times from offices, retail stores, hotels, apartment buildings and assembly properties. These observed or reported delay times provide a benchmark for estimates used in modelling other structures. Details on the activities that evacuees engaged in before and during their evacuation provide important input into the estimation of appropriate delay times.

Table E.1 presents the delay times derived from major studies. The common format used in the table was imposed on the reported data, which varied both in what was reported and how it was reported. Values that were not reported and could not be calculated are noted on the table. Although significant factors that can have affected the delay times are noted, such as poor alarm performance, time of day, weather, etc., the reader is referred to the referenced reports for complete details on the conditions under which the delay times were measured. The source of the data, i.e. survey questionnaires vs. videotaped drills, is also identified. Questionnaire data might not be as accurate as observations recorded on videotape, but it was obtained for actual fire situations. Videotaped observations can be more accurately reported, but they do not record behaviours under actual fire conditions. It is, therefore, necessary that the user exercise judgement in the use of delay times reported in the literature.

Data from experiments in a range of occupancy types have been used to provide default pre-travel activity time data for BS 7974-6:2004 [17]. These are presented in Table E.2. The data are classified into three major different behavioural scenario categories described below.

Table E.1 — Delay times derived from actual fires and evacuation exercises reported in the referenced literature

Event description	N [a]	Delay times min						Factors
		Min.	1st quartile	Median	3rd quartile	Max.	Mean	
High-rise hotel [35]	536	0	3,3	60,0	130,9	290	n/a [b]	MGM Grand Hotel fire; no alarm notification; grouped data from questionnaires
High-rise hotel [43]	47	0	2,0	5,0	17,5	120	n/a	Westchase Hilton Hotel fire; no alarm in early stages; grouped data from questionnaires
High-rise office building [36]	85	0	2,0	5,0	10,0	245	11,3	World Trade Center explosion and fire; no alarm notification (building closer to explosion)
High-rise office building [36]	46	0	4,5	10,0	31,5	185	28,4	World Trade Center explosion and fire; no alarm notification (building further from explosion)
High-rise office building[[44]	107	1,0	1,0	1,0	1,0	≈ 6,0	n/a	Fire incident; no alarms, data from interviews with occupants of four floors of building (11 interviewees were trapped)
High-rise office building [45]	12	0,5	n/a	1,0	n/a	2,3	1,2	Unannounced drill on 3 floors; data for first person to reach each of four stairwell doors to wait for voice instruction; trained staff; data from video recordings
Mid-rise office building [39]	92	0	0,4	0,6	0,8	< 4	0,6	Unannounced drill; good alarm performance; fire wardens; warm day
Mid-rise office building [39]	161	0	0,5	0,9	1,4	< 5	1,1	Unannounced drill; good alarm performance; fire wardens; cool day
One-story department store [46]	95	1	0,2	0,3	0,5	0,9	0,4	Unannounced drill; trained staff; data here derived from grouped data for 95 participants
Three-story department store [46]	122	0,05	n/a	n/a	n/a	1,6	0,6	Unannounced drill; trained staff; times distilled from analysis of videotapes
One-story department store [46]	122	0,07	n/a	n/a	n/a	1,7	0,5	Unannounced drill; trained staff; times distilled from analysis of videotapes

Table E.1 (*continued*)

Event description	N [a]	Delay times min						Factors
		Min.	1st quartile	Median	3rd quartile	Max.	Mean	
One-story department store [46]	71	0,03	n/a	n/a	n/a	1,0	0,4	Unannounced drill; trained staff; times distilled from analysis of videotapes
High-rise apartment building [4]	n/a	0	n/a	n/a	n/a	n/a	10,5	Forest Laneway fire; for occupants who attempted to evacuate in the first hour, based on questionnaire responses
High-rise apartment building [4]	219	0	n/a	187,8	n/a	720	190,8	Forest Laneway fire; for all occupants
High-rise apartment building [40]	33	0,3	0,8	1,3	4,4	10,2	2,8	Unannounced drill; good alarm performance
High-rise apartment building [40]	93	0,4	1,5	3,6	6,9	18,6	5,3	Unannounced drill; good alarm performance; heavy snow during drill
High-rise apartment building [44]	27	1,0	2,0	8,0	14,0	> 20	n/a	Fire incident in early morning; alarm functioned; fewer than half the occupants evacuated
Mid-rise apartment building [41]	42	0,6	1,0	1	3,0	> 14	2,5	Unannounced drill; good alarm performance
Mid-rise apartment building [41]	55	> 0,5	1,6	4,4	13,5	> 21	8,4	Unannounced drill; good alarm performance
Mid-rise apartment building [41]	77	> 0,3	1,9	7,7	19,1	> 24	9,7	Unannounced drill; good alarm performance
Mid-rise apartment building [41]	80	> 0,3	1,2	2,5	3,7	> 12	3,1	Unannounced drill; good alarm performance
Training facility [47]	566	<0,2	0,7	1,01	1,5	> 5	n/a	Testing sleeping subjects at a training facility

[a] Number of participants.

[b] “n/a” — not reported.

E.2 Awake and familiar

For situations where occupants are awake and familiar with the building, pre-travel activity times and pre-travel activity time distributions have been found to be very short when fire-safety management is of a high standard and staff are well trained; see References [5] and [6]. Pre-travel activity and total evacuation times have been measured on approximately 70 occasions in a range of office and laboratory buildings under different managements as part of BRE and related research programmes; see References [5], [6], [42], [37], [38], [36], [30]. Some of the data obtained from studies carried out are summarized in Table 4 of Reference [6]. Since the pre-travel activity times obtained on any one occasion can vary even within a specific building, it is neither possible nor particularly useful to present detailed data in this Technical Report.

Based on the overall data obtained, it is has been found that for well-managed cases (level M1), the first few occupants can be expected to move within a few seconds of a sounder or voice alarm. It is, therefore, proposed that a figure for the 1st percentile pre-travel activity time of 0,5 min is realistic and relatively conservative. The additional period for the last few people to move has also been found to be very short and a default period of 1 min is proposed.

For a level M2 management, occupants might not respond quite so quickly, but can be relied upon to cease their activities and evacuate in response to warnings.

Level M3 management can apply if there is some doubt about the commitment of an organization to fire-safety management and staff training.

On a small number of occasions it has been found that occupants have ignored alarms and continued their normal activities for at least several minutes, despite fire alarms sounding, until challenged.

E.3 Awake and unfamiliar

A number of video studies have been made of unannounced evacuations from stores and supermarkets as part of the BRE research programmes (see References [5], [6], [42], [37] and [38]) and studies carried out by the University of Ulster [33]. The BRE programme also included two theatres and several lecture theatre evacuations, as well as investigations of a number of fire incidents in stores; see References [5], [42], [37] and [38]. The results of these studies indicate that the pre-travel activity times of the first few occupants, and the subsequent distribution, are very short when the evacuation is well managed by trained staff. There is also some benefit from voice alarm systems over sounders; see References [5], [33], [34] and [9].

A problem with this scenario category is that occupants cannot be relied upon to evacuate unless encouraged by staff or instructed by a voice alarm system, and even this can be ignored in some cases. In at least three cases of serious store fires in the UK, large number of occupants were in the fire enclosure. Despite the fact that the growing fire and fire effluent was visible, a number of factors, including delays before starting to travel, resulted in occupants being exposed to fire effluent and a number of deaths.

While the short pre-travel activity times in Table E.2 for level M1 and level M2 management systems are considered to be reasonably good default values for well-managed and well-staffed situations, a number of studies has shown very long pre-travel activity times when occupants are unfamiliar with a building or its systems and are not managed by trained staff.

Examples include the Equinox office building study, where unfamiliar occupants took approximately 11 min to respond to a sounder; see Reference [34], the clothing store fire, where shoppers and staff failed to evacuate for 4 min to 5 min until fire and smoke made conditions untenable; see Reference [5] and the Tyne and Wear Underground station studies, in which occupants ignored a sounder for up to 9 min; see Reference [9]. In the Equinox and Tyne and Wear studies, better results were obtained when voice alarm messages were used, but with increasing use of such systems in recent years, this is not always found to be the case.

On the basis of these studies, short 1st and 99th percentile default pre-travel activity times are proposed for level M1 and level M2 managed occupancies. It is suggested that some extra time be added for way-finding in more complex buildings. Where efficient emergency management cannot be guaranteed, pre-travel activity times become much longer and more variable. An approximate default time of 15 min for the 1st percentile plus a further 15 min for the 99th percentile is suggested.

E.4 Sleeping

With all forms of sleeping scenarios, it is difficult to obtain short pre-travel activity times; see References [5], [35], [4], [40], [41]. Occupants might or might not be roused by alarms and might require a considerable time to prepare themselves and decide to evacuate.

There are few detailed studies of pre-travel activity times in sleeping accommodation; see Reference [35]. Reports from a number of incidents in hotels or hostels have shown that occupants might require many minutes to evacuate; see Reference [4]. In a least one case where times have been reported, although the first quartile moved after 3 min, the third quartile required 131 min; see References [35] and [4].

Due to the long periods reported and their extreme variability, it can be necessary to use very conservative default times. For occupants close to the fire, within a private dwelling, it is considered that design pre-travel activity times could be as short as 5 min to 10 min for well-managed situations (where occupants have well-maintained smoke detectors and a family fire game plan); see Reference [39]. In practice, flaming fires can produce lethal conditions within this time period, so it is necessary that individual response times be shorter in many cases. There is, however, an annual rate of approximately 6 000 smoke exposure injuries in dwellings.

Table E.2 — Suggested pre-travel activity times for different design behavioural scenario categories

Scenario category and modifier levels [a]	First occupants t_{pre} (1st percentile)	Occupant distribution t_{pre} (99th percentile)
A: Awake and familiar		
M1 B1 – B2 A1 – A2 [a]	0,5	1,5
M2 B1 – B2 A1 – A2	1	3
M3 B1 – B2 A1 – A3	> 15 [b]	> 30 [b]
For B3, add 0,5 for way-finding.	—	—
M1 normally requires a voice alarm/PA if unfamiliar visitors likely to be present.	—	—
B: Awake and unfamiliar		
M1 B1 A1 – A2	0,5	2,5
M2 B1 A1 – A2	1,0	4,0
M3 B1 A1 – A3	> 15 [b]	> 30 [b]
For B2, add 0,5 for way-finding.	—	—
For B3, add 1,0 for way-finding.	—	—
M1 normally requires a voice alarm/PA.	—	—
Ci: Sleeping and familiar (e.g. dwellings, individual occupancy)		
M2 B1 A1	5 [b]	10 [b]
M3 B1 A3	10 [b]	> 40 [b]
For other units in a block, assume 1 h.	—	—
Cii: Managed occupancy (e.g. serviced apartments, hall of residence)		
M1 B2 A1 – A2	10 [b]	30 [b]
M2 B2 A1 – A2	15 [b]	40 [b]
M3 B2 A1 – A3	> 20	> 40
Ciii: Sleeping and unfamiliar (e.g. hotel, boarding house)		
M1 B2 A1 – A2	15 [b]	30 [b]
M2 B2 A1 – A2	20 [b]	40 [b]
M3 B2 A1 – A3	> 20 [b]	> 40 [b]
For B3, add 1,0 for way-finding.	—	—
M1 normally requires a voice alarm/PA.	—	—

Table E.2 (*continued*)

Scenario category and modifier levels [a]	**First occupants** t_{pre} (1st percentile)	**Occupant distribution** t_{pre} (99th percentile)
D: Medical care:		
Awake and unfamiliar (e.g. day centre, clinic, surgery, dentist)		
M1 B1 A1 – A2	0,5	2
M2 B1 A1 – A2	1,0	3
M3 B1 A1 – A3	> 15	> 15
For B2, add 0,5 for way-finding.	—	—
For B3, add 1,0 for way-finding.	—	—
M1 normally requires a voice alarm/PA.	—	—
Sleeping and unfamiliar (e.g. hospital ward, nursing home, old people's home)		
M1 B2 A1 – A2	—	—
M2 B2 A1 – A2	5	10 [c]
M3 B2 A1 – A3	10	20 [c]
For B3, add 1,0 for way-finding.	> 10	> 20 [c]
M1 normally requires a voice alarm/PA.	—	—
E: Transportation: Awake and unfamiliar (e.g. railway or bus station or airport)		
M1 B3 A1 – A2	—	—
M2 B3 A1 – A2	1,5	4
M3 B3 A1 – A3	2,0	5
M1 and M2 normally require a voice alarm/PA.	> 15	> 15

NOTE There is a lack of data on evacuation behaviour and the times required for key aspects of evacuation. Therefore, it is necessary to bear in mind these limitations when proposing or assessing designs incorporating engineered solutions in relation to human behaviour.

In particular, it is necessary that the database be improved by the provision of information, such as evacuation time records, video records from real evacuation incidents (including fires) and data from monitored evacuations in a reasonably large set of each occupancy type, including sleeping accommodation. This can, then, provide a definitive database for design applications and for the further development of predictive evacuation and behaviour models.

[a] M indicates level of fire safety management; B indicates level of building complexity; A indicates level of alarm system; see Annex D.

[b] Figures with greater levels of uncertainty.

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

For sleeping and unfamiliar scenarios, such as sleeping accommodation in hotels (especially at night), it is considered that occupants cannot be relied upon to evacuate efficiently without management intervention. Even for a well managed occupancy with a well designed warning system, it is suggested that a default 1st percentile pre-travel activity time of 15 min can be appropriate. For managed occupancies, somewhat shorter times can be appropriate if occupants are well trained.

Different forms of medical-care occupancies also have particular characteristics, influencing both pre-travel activity time distributions and travel time distributions. Studies of well managed outpatient clinics (attended by ambulatory patients), have shown short pre-travel activity time distributions, similar to category B; see References [5] and [48]. Elderly occupants of residential nursing homes have, in some cases, shown good responses to alarms, with relatively short response times, but in other incidents, many occupants have been unable or unwilling to evacuate. Where staff are well trained, but likely to be few in number compared to the number of occupants requiring active assistance with evacuation (especially at night), relatively long pre-travel activity time distributions can be predicted.

Category E (transport facilities) are a special case of category B (awake and unfamiliar) but special factors likely to influence pre-travel activity time distributions include the considerable spatial complexity, language difficulties, unwillingness to leave luggage, family groups and complex security issues.

Annex F
(informative)

Evacuation start time of the verification methods for safe evacuation in Japan

F.1 General

This Annex outlines a method used in Japan for specifying "start time" for design purposes. It is presented here for information as an example of an approach used, and is not intended as normative. As a result of the reform of the Building Standard Law in Japan in 2000 [49], the verification methods for safe evacuation were introduced. The calculation methods of the required time for starting to escape, travelling to an exit, passing through an exit, and smoke spread are described in the Japan Ministry of Construction Notification No. 1441 and No. 1442 (May 31, 2000) [50]. In this Annex, the calculation methods for evacuation start time are translated from these Notifications.

This represents a prescriptive system, specifying a specific assumed "start time," t_{start}, required for particular situations. The basic concept is illustrated by Equation (F.1).

$$t_{start} = t_1 + t_2 \tag{F.1}$$

where

t_1 is the time for transferring information of the fire, e.g., sound, noise, smoke, smell, flame, alarm, etc., which depend on the location, e.g. fire room, fire floor/other floor;

t_2 is the time for initial response before escape, e.g. researching, fighting the fire, dressing, investigating, which depend on the occupancy type and whether the occupants are awake or asleep.

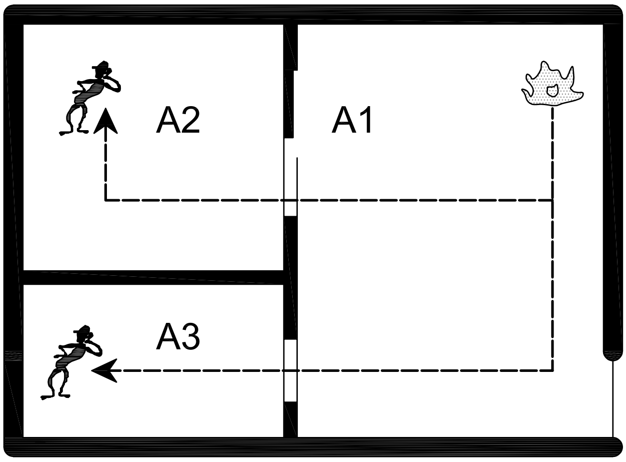
In this context, the "start time" represents the time from ignition to that when occupants start to enter their travel phase. This is assumed to depend on the location of occupants relative to the fire (in room of origin, floor of origin or several floors of the building whose occupants are required to pass through the affected area), the area of the location (room, floor or several affected floors) and the type of occupancy (with slightly longer times for sleeping accommodation). This, therefore, embraces the concept that a longer time can elapse before occupants become aware of a fire in larger and more complex spaces and with a progressively more remote location from the fire. It also embraces the concept that occupants require time to engage in a range of behaviours before starting to travel to the exits and that this time is likely to be longer in a sleeping accommodation. The method makes no allowance for the effects of the warning system, the fire-safety management system or familiarity of the occupants with the building. It is also assumed that occupants start to evacuate immediately if they see flames or smoke.

F.2 For a room evacuation

The time, $t_{start,rm}$, expressed in minutes, required for occupants in a room to begin to evacuate after the start of the fire, stipulated in Article 129-2, paragraph 3, item (1) a. of the Building Standard Law Enforcement Order (hereinafter referred to as "the Order") shall be calculated as given by Equation (F.2):

$$t_{start,rm} = \frac{\sqrt{\sum A_{area}}}{30} \tag{F.2}$$

where A_{area} is the floor area of the said habitable room and of each part or parts of the building that cannot be evacuated without passing through the said habitable room (hereinafter referred to as "said habitable room, etc."), expressed in units of square metres; see Figure F.1.



a) The area considered for calculating the evaluation time for fire room A1 is equal to the areas of rooms A1 plus A2 plus A3.

b) The area considered for calculating the evaluation time for fire room A2 is equal just to the area of room A2.

Figure F.1 — Definition of the area of a fire room for evaluation of evacuation start time

F.3 For a floor evacuation

The time, $t_{start,fl}$, expressed in minutes, required for occupants on a floor to begin to evacuate after the start of the fire stipulated in Article 129-2, paragraph 3, item (4) a. of the Order shall be calculated as given by Equation (F.3) for apartment houses, hotels, or other similar buildings (excluding hospitals, clinics and children's welfare facilities, etc.), and by Equation (F.4) for other buildings (excluding hospitals, clinics and children's welfare facilities, etc.):

$$t_{start,fl,1} = \frac{\sqrt{\sum A_{floor}}}{30} + 5 \qquad (F.3)$$

$$t_{start,fl,2} = \frac{\sqrt{\sum A_{floor}}}{30} + 3 \qquad (F.4)$$

where A_{floor} is the total floor area of the parts of the building that cannot be evacuated without passing through each room of the said floor and through the exit to the through stairs on the said floor (hereinafter referred to as "each room, etc. of the said floor"), expressed in square metres.

F.4 For a total evacuation

The time, $t_{start,tot}$, expressed in minutes, required for occupants in a building to begin to evacuate after the start of the fire stipulated in Article 129-2-2, paragraph 3, item (2) a. of the Building Standard Law Enforcement Order (hereinafter referred to as "the Order") shall be calculated as given by Equation (F.5) for apartment houses, hotels, or other similar buildings (excluding hospitals, clinics and children's welfare facilities, etc.) and by Equation (F.6) for other buildings (excluding hospitals, clinics and children's welfare facilities, etc.):

$$t_{start,tot} = \frac{2\sqrt{\sum A_{floor}}}{15} + 5 \qquad (F.5)$$

$$t_{start,tot} = \frac{2\sqrt{\sum A_{floor}}}{15} + 3 \qquad (F.6)$$

where A_{floor} is the total of the floor areas of parts of the building that cannot be evacuated without passing through each room of the said floor and through the said floor, expressed in square metres.

Annex G
(informative)

Guidance on travel speeds and flow rates

G.1 General

Data on the relationships between occupant density, travel speeds and flow rates on horizontal escape routes and on stairs (descending and ascending) for ranges of exit and stair widths is derived from research carried out mainly in the United Kingdom, the United States, Canada, Japan and Russia. The results have been incorporated into calculation methods widely used for fire engineering design, which are described in detail in the SFPE Handbook of Fire Protection Engineering; see References [10] and [11].

There are three fundamental characteristics of crowd movement: density, speed and flow. Density of a crowd is defined as the number of persons per unit area, e.g., 2,0 persons/m^2. Density can also be expressed as the area per person, e.g., 0,5 m^2/person. Speed is the rate of motion of the occupants, usually expressed in metres per second. Flow is the rate at which people pass a particular point, such as a doorway, per unit of time, e.g. 2,0 persons/s.

The results from work on horizontal and vertical travel speeds and flow rates from a range of studies leading to the current calculation methods used for fire engineering are summarized in Clauses G.2 to G.5. Data are also shown for people with impaired mobility.

The requirements of computer simulation models for evacuation developed over recent years have lead to a re-examination of the fundamental aspects of occupant movement through building spaces and revealed a number of deficiencies and variations in data for some basic parameters. Thus, basic data for maximum flow rates through horizontal and vertical escape routes show a considerable range of variation, both in terms of published experimental data for different populations and assumed data used in building codes and guidance for fire engineering calculations. Other parameters, such as merge ratios where two streams of evacuating occupants meet (for example at storey exits into stairs), densities taken up by evacuating occupants in different situations and effects of opposing flows, have barely been addressed, despite the considerable effects such parameters can have on evacuation flows and evacuation flow times; see Reference [14].

G.2 Effective width concept

Persons moving through the exit routes of a building maintain a boundary layer clearance from walls and other stationary obstacles they pass. This clearance is needed to accommodate lateral body sway and assure balance.

Discussion of this crowd movement phenomena is found in the works of Pauls, as reviewed in Proulx [10], Fruin [51] and Habricht and Braaksma [52]. The useful (effective) width of an exit path is the clear width of the path less the width of the boundary layers. Table G.1 is a list of boundary layer widths. The effective width of any portion of an exit route is the clear width of that portion of an exit route less the sum of the boundary layers.

Clear width is measured

a) from wall to wall in corridors or hallways;

b) as the width of the treads in stairways;

c) as the actual passage width of a door in its open position;

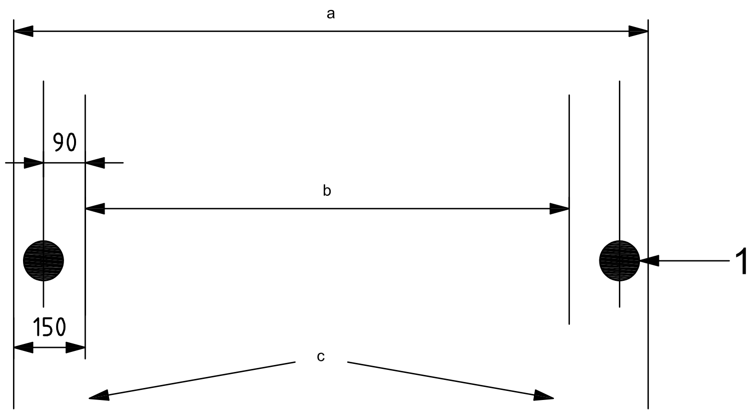
d) as the space between the seats along the aisles of an assembly arrangement;

e) as the space between the most intruding portions of the seats (when unoccupied) in a row of seats in an assembly arrangement.

The intrusion of handrails is considered by comparing the effective width without the handrails, and the effective width using a clear width from the edge of the handrail. The smaller of the two effective widths then applies. Using the values in Table G.1, it is necessary to consider only handrails that protrude more than 6 cm. Minor mid-body height or lower intrusions such as anti-panic closures are treated in the same manner as handrails. Where an exit route becomes either wider or narrower, only that portion of the route has the appropriate greater or lesser clear width.

Pauls has carried out extensive research into multi-storey building evacuations, including 58 experimental high-rise building evacuations; see Reference [56] and review in Proulx [10]. Unlike earlier models developed for the prediction of total evacuation times proposed by Togawa [53], Melinek and Booth [54], and Predtechenskii and Milinskii [55], Pauls' principal approach has been to carry out building evacuations and fit a simple equation to the empirical data. In doing so, Pauls observed that flow rate on stairs is a linear function of width (i.e. that it is related to incremental increases in width and not to “unit widths”). Pauls also found that the best fit with the data is obtained using the concept of “effective width”. This boundary layer is constant and, therefore, has a greater influence on flow rate calculations for narrow escape routes than for wider ones. Both the incremental-width-vs-flow-rate relationship and the effective-width model have been generally adopted for engineering calculations and used for the development of general flow-calculation methods described by Nelson and Mowrer in the SFPE Handbook [11]. The effective-width concept is illustrated in Figure G.1 with the boundary-layer data for a range of building elements shown in Table G.1.

Dimensions in millimetres



Key

1 handrail

a Nominal stair width.

b Effective width.

c Area of tread use.

Figure G.1 — Effective width for a stair (after Pauls [56])

Table G.1 — Boundary layer widths

Exit route element	Boundary layer mm
Theatre chairs, stadium benches	0
Railings, handrails [a]	89
Obstacles	100
Stairways, doors, archways	150
Corridor, ramp walls	200
Wide concourses, passageways	460

[a] Where handrails are present, use the value resulting in the lesser effective width.

G.3 Horizontal travel speeds

Observations and experiments have shown that the evacuation speed of a group is a function of the population density. It also differs between horizontal and vertical travel. Guidance on the effects of occupant density on walking speed is presented in Nelson and Mowrer [11]. If the population density is less than 0,54 persons/m^2 of exit route, individuals move at their own pace, independent of the speed of others. Movement is considered to cease when population density exceeds 3,8 persons/m^2.

Unimpeded walking speeds are typically quoted as being around 1,2 m/s. For example, Pauls [56] quotes 1,25 m/s, based on empirical studies in office buildings. Nelson and Mowrer [11] quote 1,19 m/s; their method is derived from the work of Fruin [51], Pauls, as reviewed in Proulx [10], and Predtechenskii and Milinskii [55].

Ando, *et al*. [57] studied travellers in railway stations and found that unimpeded walking speed varied with age and sex. The speed/age distributions for males and females were unimodal and positively skewed, both peaking at around 20 years of age (males at about 1,6 m/s and females at about 1,3 m/s).

Thompson and Marchant [12] developed new techniques for analysing video footage of crowd movement, and derived a method for modelling the movement of individual people based on the interpersonal distance between them. From this work, Thompson and Marchant suggested that the “interference threshold” be 1,6 m, such that when the separation between individuals is greater than this, their walking velocity is unaffected. They quote unimpeded walking speeds of around 1,7 m/s for males and 0,8 m/s for females (the median value being 1,4 m/s). According to this model, the velocity decreases as the interpersonal distance decreases (below 1,6 m), reaching zero when the individuals are tightly packed, such that the interpersonal distance is equal to their body depth.

Nelson and Mowrer [11] derived Equation G.1 for the relationship between the speed, S, along the line of travel, expressed in metres per second, and the density between the limits of 0,54 persons/m^2 and 3,8 persons/m^2; see Table G.2:

$$S = k - akD \tag{G.1}$$

where

D is the density, expressed as persons per square metre;

k is equal to 1,4 for horizontal travel;

a is equal to 0,266.

G.4 Vertical travel speeds

Ando, *et al.* [57] quoted unimpeded velocities on stairs of about 0,8 m/s for travel downwards and 0,7 m/s for travel upwards.

Fruin [51] (cited in Galea, *et al.* [19]) presented a range of values for travel speed on stairs, according to age and sex. For travel downwards, these ranged from 1,01 m/s for males under 30 years, to 0,595 m/s for females aged over 50. For travel upwards, they ranged from 0,67 m/s for males under 30, to 0,485 m/s for females over 50. Fruin's figures are calculated from observations made on two staircases, one with 18 cm (7 in) risers and 28,5 cm (11,25 in) treads, and one with 15 cm (6 in) risers and 30,5 cm (12 in) treads. Travel speeds up and down were faster for the stairs with the smaller rise height.

Nelson and Mowrer [11] present travel speeds for four different stair designs of rise height between 16,5 cm and 19 cm (6,5 in and 7,5 in), and tread between 25,5 cm and 33 cm (10 in and 13 in). They give travel speeds ranging from 0,85 m/s to 1,05 m/s, with speed increasing as rise height decreases. There was no differentiation between upwards and downwards travel, nor were the data broken down by sex and age.

The effects of density on vertical travel speeds can be calculated using Equation (G.1) using different values for k, as shown in Table G.2.

Table G.2 — Maximum unimpeded travel speeds and flow rates for horizontal and stair travel

Exit route element		k [a]	Travel speed m/s	Maximum specific flow F_{Smax} persons/m/s of effective width
Corridor, aisle, ramp, doorway		1,40	1,19	1,19
Stair riser mm	Stair tread mm	—	—	—
191	254	1,00	0,85	0,94
178	279	1,08	0,95	1,01
165	305	1,16	1,00	1,09
165	330	1,23	1,05	1,16

[a] Constants for Equation (G.1), effects of density on travel speed.

Within the range listed in Table G.2, the evacuation speed on stairs varies approximately as the square root of the ratio of tread width to tread height. There are insufficient data to appraise the likelihood that this relationship holds outside this range.

G.5 Maximum flow rates for horizontal and vertical escape routes

G.5.1 Calculation of flow rates

Table G.3 shows a summary of maximum measured exit flow rates from the literature (reproduced from Thompson and Marchant [12]).

Pauls has suggested that the derivation of the higher flow rate limits shown in Table G.3 might not be truly representative of actual building evacuations. Higher flow rates are reported for sites such as streets or sports grounds.

Below the maximum flow capacity, flow rates depend on occupant density and travel speeds. The equation for specific flow, F_S, i.e., the number of persons evacuating past a point per metre of effective width per second, is shown as Equation (G.2):

$$F_S = SD \quad \text{(G.2)}$$

where

D is the density;

S is the speed.

Combining Equations (G.1) and (G.2) gives Equation (G.3):

$$F_S = (1 - aD)kD \quad \text{(G.3)}$$

where k is obtained from Table G.2.

As the population density increases, specific flow increases up to a maximum density of 1,9 persons/m^2. At higher densities, the flow rate falls off to zero at 3,77 persons/m^2.

Maximum specific flow rates for stairs are shown in Table G.2. As stated, flow rates are considered to be affected by boundary layers, which should be subtracted from the actual width of a corridor, doorway, or stair according to Table G.2. For any particular point in an exit route, the calculated flow rate, F_c, is the specific flow rate multiplied by the effective width, as given by Equation (G.4).

$$F_c = F_S \times W_e \quad \text{(G.4)}$$

where W_e is the effective width, expressed in metres.

Table G.3 — Summary of maximum flow rates [a]

Source	**Maximum design flow** persons/m/s	**Ultimate flow capacity** persons/m/s	Comments
BS 5588-11, derived from French, British and American studies, pre-1947 [58]	1,33 [b]	—	Standard British code for buildings
SCICON report [59]	1,37	—	Data from football crowds
Guide to Safety in Sports Grounds [60]	1,82 [c]	—	Based on Japanese data and derived from 60 persons/0,55 m/min unit exit width calculation
Hankin and Wright [61]	1,48	1,92	Commuters on the London Underground
Fruin [51]	1,37	4,37	Max. flow is a peak regimented, “funnelled” flow under pressure
Daly [62]	1,43	—	For underground stations
Ando, *et al.* [63]	—	1,7 to 1,8	Japanese commuters at railway stations
Fire and Buildings, The Aqua Group [64]	1,5	—	General design text
Predtechenskii and Milinskii [55]	—	1,83	“Emergency conditions” for adults in mid-season dress
SFPE Handbook, (Nelson and Mowrer) [11]	1,3 [d]	—	2 × 0,15 m boundary layers deducted from width of exit
Polus, *et al.* [65]	1,25 to 1,58	1,58	Pedestrian movement on sidewalks in Israel

[a] Reproduced from Thompson and Marchant [12].

[b] Derived from exit capacities.

[c] Unit exit width method.

[d] Effective width method.

Time for passage, t_p, i.e., time for a group of persons to pass a point in an exit route, expressed in minutes, is given by Equation (G.5):

$$t_p = P/F_c \tag{G.5}$$

where

F_c is the flow rate, expressed as persons/min;

P is population, expressed as the number of persons.

G.5.2 Transitions

Transitions are any point in the exit system where the character or dimension of a route changes or where routes merge. Typical examples of points of transition include

a) any point where an exit route becomes wider or narrower, e.g., a corridor can be narrowed for a short distance by an intruding service counter or similar element; the calculated density, D, and specific flow, F_S, differ before reaching, while passing and after passing the intrusion;

b) the point where a corridor enters a stairway; there are actually two transitions: one occurs as the egress flow passes through the doorway, the other as the flow leaves the doorway and proceeds onto the stairs;

c) the point where two or more exit flows merge, e.g., the meeting of the flow from a cross aisle into a main aisle that serves other sources of exiting population; it is also the point of entrance into a stairway serving other floors.

The calculation model presented in this Annex is described in more detail in the SFPE Handbook [11]. It is based on the simple algebraic concept that the maximum flow rates into and out of a point where a route widens or narrows, or where two routes merge into one, are a function of the relative maximum specific flows and effective widths of the various elements. Thus when a route widens or narrows, the total flow rate, F_c, into and out of the "pinch" point is the same and the limiting factor is the maximum specific flow rate, F_{Smax}, sustainable for the narrowest element.

Where two routes merge into one, it is assumed that the maximum calculated flow rate is also limited by the maximum specific flow rates and width of either the two inlets or the outlet, whichever is the limiting factor. The proportion of the flow from each inlet is assumed to be proportional to the ratio of the effective widths, W_e, of the two inlet elements. Based on experimental and computer simulation modelling studies (see Reference [14]), this assumption is considered to represent a somewhat simplistic model. At merge points between flows entering at storey exits with flows down stairs, it has been found that merge ratios tended to be 50:50, even when the stair and exit widths were somewhat different (but with comparable proportions). It is considered that the merge from the storey exit is facilitated by the fact that the stair flows turn through 180° at a landing, tending to take the shortest line and allowing occupants from the storey exit to enter the stairs. However, in situations such as in a long horizontal corridor with route entering at 90°, it is considered likely that the corridor flow is dominant and that the rate of entry from the side route can be impeded. These issues of potential flow dominance and deference behaviour are discussed in Clause 10. In situations where merge rates are considered related to the effective width of converging elements (for example, where the width of one entry is much greater than the other), the maximum flow rates may be estimated by the method described in this subclause.

The following rules apply to determining the densities and flow rates following the passage of a transition point.

a) The flow after a transition point is a function, within limits, of the flow(s) entering the transition point.

b) The calculated flow, F_c, following a transition point cannot exceed the maximum specific flow, F_{Smax}, for the route element involved multiplied by the effective width, W_e, of that element.

c) Within the limits of rule b, the specific flow, F_S, of the route departing from a transition point can be determined for the following cases.

   1) The specific flow departing from transition point, $F_{s(out)}$, for cases involving one flow into and one flow out of a transition point, is calculated as given in Equation (G.6):

$$F_{S(out)} = F_{S(in)} W_{e(in)} / W_{e(out)} \qquad (G.6)$$

   where

   $F_{S(in)}$ is the specific flow arriving at transition point;

   $W_{e(in)}$ is the effective width prior to transition point;

   $W_{e(out)}$ is the effective width after passing transition point.

   2) The specific flow departing from transition point, $F_{s(out)}$, for cases involving two incoming flows and one outflow from a transition point, such as that which occurs with the merger of a flow down a stairwell and the entering flow at a floor, is calculated as given in Equation (G.7):

$$F_{S(out)} = \left\{ \left[F_{S(in-1)} W_{e(in-1)} \right] + \left[F_{S(in-2)} W_{e(in-2)} \right] \right\} / W_{e(out)} \qquad (G.7)$$

   where the subscripts (in–1) and (in–2) indicate the values for the two incoming flows.

3) The specific flow departing from transition point for cases involving other merger geometries can be calculated from the general relationship given in Equation (G.8):

$$\left[F_{\text{S(in}-1)}W_{\text{e(in}-1)}\right]+\ldots+\left[F_{\text{S(in}-n)}W_{\text{e(in}-n)}\right]=\left[F_{\text{S(out}-1)}W_{\text{e(out}-1)}\right]+\ldots+\left[F_{\text{S(out}-n)}W_{\text{e(out}-n)}\right] \quad \text{(G.8)}$$

where n in the subscripts (in–n) and (out–n) is a number equal to the total number of routes entering (in–n) or leaving (out–n) the transition point.

d) Where the calculated specific flow, F_{S}, for the route(s) leaving a transition point, as derived from the equations in rule c, exceeds the maximum specific flow, F_{Smax}, a queue will form at the incoming side of the transition point. The number of persons in the queue will grow at a rate equal to the calculated specific flow, $F_{\text{S(in)}}$, in the arriving route minus the calculated flow leaving the route through the transition point.

e) Where the calculated outgoing specific flow, $F_{\text{S(out)}}$, is less than the maximum specific flow, F_{Smax}, for that route(s), there is no way to predetermine how the incoming routes merge. The routes can share access through the transition point equally, or there can be total dominance of one route over the other. For conservative calculations, it is necessary to assume that the route of interest is dominated by the other route(s). If all routes are of concern, it is necessary to conduct a series of calculations to establish the bounds on each route under each condition of dominance.

G.5.3 Empirically-based method for estimation of total evacuation flow time for a multi-storey building

Pauls has carried out extensive research into multi-storey building evacuations, including 58 experimental high-rise building evacuations; see References [10,56]. His empirically-based model describes the flow, F, of people along a stairwell as a function of the effective width. Pauls reports that when the density, D, is less than 0,5 persons/m^2, people are able to move on the level at 1,25 m/s. At densities of 4 persons/m^2 to 5 persons/m^2, equivalent to a fairly crowded lift, movement speed is greatly reduced. On stairs, at low densities, relatively fit people can average about 1,1 m/s along a stair slope. Equation (G.9) was derived for stairs:

$$F = 1{,}26D - 0{,}33D^2 \quad \text{(G.9)}$$

Under ideal conditions,

— each person would occupy slightly less than two treads, at a density of 2 persons/m^2;

— there is a descent rate of one storey every 15 s, at a speed of 1,25 m/s along the slope;

— the flow rate is 1,18 persons/m/s of effective stair width.

The optimum flow down stairs is, therefore, 1,18 persons/m/s effective width. Pauls' data are based on measurements obtained from evacuation drills, primarily in office buildings ranging from 8 stories to 21 stories high. Pauls observed evacuation time, t_{min}, varying from approximately 10 s per story for buildings with small populations to approximately 20 s per story for buildings with large populations. The evacuation equations for t, the minimum time, expressed in minutes, to complete an uncontrolled total evacuation by stairs, were developed for the indicated range. Equation (G.10) applies to the prediction of evacuation times in buildings with large populations exceeding 800 persons per metre of effective stair width:

$$t_{\text{min}} = 0{,}70 + 0{,}0133p \quad \text{(G.10)}$$

where p is the actual evacuation population per metre of effective stair width, measured immediately above the discharge level of the stair.

It should be recognized that "effective stair width", as used by Pauls, is defined in the following manner:

"This empirically based model describes flow as a linear function of a stair's effective width: the width remaining once the edge effects are deducted [150 mm (6 in) from each wall boundary and 90 mm (3,5 in) from each handrail centreline]. It takes into account the propensity of people to sway laterally, especially when walking slowly in a crowd and, therefore, to arrange themselves in a staggered traditional unit-width model based on presumed static dimensions of people's shoulders."

Equation (G.11) applies to the prediction of evacuation times in buildings with a population of fewer than 800 persons per metre of effective stair width:

$$t_{\text{min}} = 2{,}00 + 0{,}011\,7p \tag{G.11}$$

where p is the actual evacuation population per metre of effective stair width (actual width minus 0,3 m).

Pauls also examined the relationship between the speed or velocity of evacuation and the density on the stairs during the uncontrolled total evacuation. It should be remembered that this movement is in the vertical, downward direction.

Based upon his study of experimental evacuation flow times from 58 high-rise buildings, Pauls derived a general equation for t, the minimum time, expressed in minutes, to complete an uncontrolled total evacuation by stairs, as given in Equation (G.12):

$$t_{\text{min}} = 0{,}68 + 0{,}081p^{0{,}73} \tag{G.12}$$

The predictive curve has a net error in predicting total simultaneous evacuation travel times in buildings of 8 stories to 15 stories of 0,2 %.

G.5.4 Effect of impaired mobility and other factors on travel speed

Movement speeds measured and reported in the literature mostly date from some years ago. The demographics of populations are changing, with an increase in obesity and in the proportion of elderly persons with somewhat reduced physical abilities. It is, therefore, possible that the actual speeds at which people travel on horizontal surfaces or go up and down stairwells are changing somewhat over the years (and in different parts of the world). The inclusion of persons with restricted mobility is important, for example, the inclusion of the effect on the speed of movement of a family group that is likely determined by the slowest member, or the speed of movement of a person who walks with a cane.

Several factors have an impact on the speed of movement, including the characteristics of the occupants, such as age, gender, grouping, clothing and physical ability. The environmental conditions, such as the presence of a crowd, smoke or emergency lighting, are also important. The stairwell or corridor design, dimensions and covering can also play an important role in the speed of movement. The presence of fire effluent is also likely to affect movement speed as discussed. All these factors are rarely considered in evacuation models. Table G.4 presents the travel speeds reported in the studies referenced in Thompson and Marchant [12]. Table G.4 presents some data obtained from studies of travel speeds of mobility impaired populations; see References [13] and [66].

Table G.4 — Travel speeds reported in the referenced literature

Type of situation		Measured travel speeds m/s (ft/min)				
Population density is reportedly not a factor	Transport terminals [51]	1,35 (265) on walkways				
	Average under “normal conditions” [55]	1,0				
	Experiment with disabled subjects [13]	**Min.**	**1st quartile**	**3rd quartile**	**Max.**	**Mean**
	On horizontal surfaces:					
	All disabled subjects	0,10	0,71	1,28	1,77	1,00
	With locomotion disability	0,10	0,57	1,02	1,68	0,80
	No aid	0,24	0,70	1,02	1,68	0,95
	Crutches	0,63	0,67	1,24	1,35	0,94
	Cane	0,26	0,49	1,08	1,60	0,81
	Walker/rollator	0,10	0,34	0,83	1,02	0,57
	Without locomotion disability	0,82	1,05	1,34	1,77	1,25
	Unassisted wheelchair	0,85	—	—	0,93	0,89
	Assisted ambulant	0,21	0,58	0,92	1,40	0,78
	Assisted wheelchair	0,84	1,02	1,59	1,98	1,30
	On upward incline:					
	All disabled subjects	0,21	0,42	0,74	1,32	0,62
	With locomotion disability	0,21	0,42	0,72	1,08	0,59
	No aid	0,30	0,48	0,87	1,08	0,68
	Crutches	0,35	—	—	0,53	0,46
	Cane	0,21	0,38	0,70	1,05	0,52
	Walker/rollator	0,30	—	—	0,42	0,35
	Without locomotion disability	0,70	—	—	1,32	1,01
	Unassisted wheelchair	0,70	—	—	—	—
	Assisted ambulant	0,23	0,42	0,70	0,72	0,53
	Assisted wheelchair	0,53	0,70	1,05	1,05	0,89
	On downward incline:					
	All disabled subjects	0,10	0,42	0,70	1,83	0,60
	With locomotion disability	0,10	0,42	0,70	1,22	0,58
	No aid	0,28	0,45	0,94	1,22	0,68
	Crutches	0,42	—	—	0,53	0,47
	Cane	0,18	0,35	0,70	1,04	0,51
	Walker/rollator	0,10	—	—	0,52	0,36
	Without locomotion disability	0,70	—	—	1,83	1,26
	Unassisted wheelchair	1,05	—	—	—	—
	Assisted ambulant	0,42	0,52	0,86	1,05	0,69
	Assisted wheelchair	0,70	0,96	1,05	1,05	0,96

Table G.4 (*continued*)

Type of situation		Measured travel speeds m/s (ft/min)	
Population density is reportedly not a factor	Mid-rise apartment drill [41]	0,47 on stairs (ranged from 0,34 to 1,08 among various adult age groups; one visually impaired person travelled 0,31)	
	Mid-rise apartment drill [41]	0,44 on stairs (ranged from 0,32 to 0,56 among various adult age groups)	
	Mid-rise apartment drill [41]	0,41 on stairs (ranged from 0,30 to 0,47 among various adult age groups)	
	High-rise apartment drill [40]	1,05 (ranged from 0,57 to 1,20 among various adult age groups)	
	High-rise apartment drill [40]	0,95 (ranged from 0,56 to 1,12 among various adult age groups)	
Population density is a factor	Public places [51]	0,51 to 1,27 (100 to 250) on walkways	
		0,36 to 0,76 (70 to 150) on stairs	
	Public places [55]	0,28 (17 m/min) minimum on horizontal surfaces	
		0,18 to 0,27 (11 to 16 m/min) down stairs	
	Theatres and educational centres [55]	0,25 to 0,3; max 2,33 (15 to 20 m/min)	
	Industrial buildings [55]	0,42 to 0,56; max 2,33 (25 to 30 m/min)	
	Transport terminals [55]	0,33 to 0,83; max 2,10 (20 to 25 m/min)	
	Descending stairs [55]	0,33 to 0,42; max 1,28 (20 to 25 m/min)	
	High-rise office building drill: [45]	**Mean speed** m/s	**Density** persons/m^2
	stairs with full lighting	0,61	1,30
	stairs with reduced lighting	0,70	1,25
	stairs with photoluminescent material (PLM) installation and reduced lighting	0,72	1,00
	stair with PLM only	0,57	2,05

Table G.4 (*continued*)

Type of situation		Measured travel speeds m/s (ft/min)					
	Mid-rise office building drill [39]	0,78 down stairs					
	Mid-rise office building drill [39]	0,93 down stairs					
	Hotel exercise – speed along corridor [67]	**Min.**	**1st quar-tile**	**Med.**	**3rd quar-tile**	**Max.**	**Mean**
	Daytime scenario 1:						
	able-bodied participants	0,6	1,1	1,3	1,8	4,0	1,5
	wheelchair users	0,2	—	—	—	1,2	0,8
	walking disabled	0,1	—	—	—	—	—
	Daytime scenario 2:						
	able-bodied participants	0,3	0,9	1,1	1,3	1,6	1,1
	wheelchair users	0,4	—	—	—	0,7	0,6
	walking disabled	0,7	—	—	—	—	—
	Night-time scenario:						
	able-bodied participants	0,5	1,1	1,3	1,7	3,8	1,5
	wheelchair users	0,5	—	—	—	0,9	0,7
	walking disabled	2,4 [a]	—	—	—	—	—

[a] This person travelled at this speed for a distance of 4,9 m.

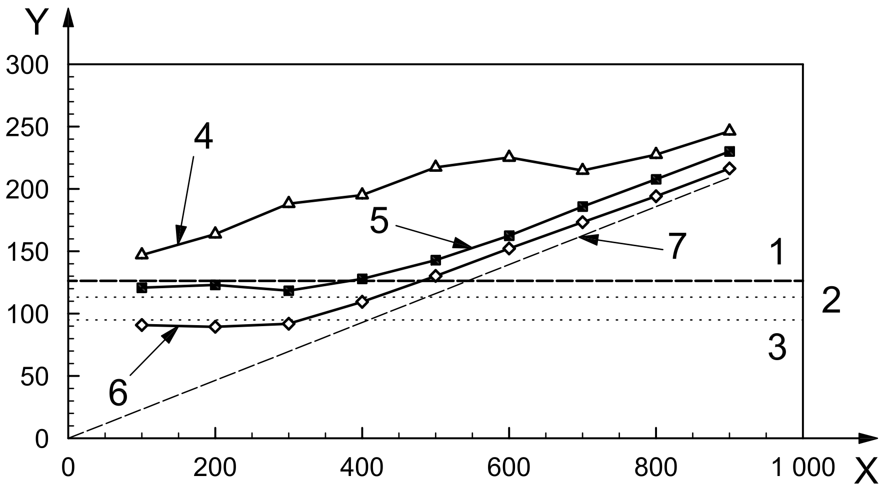
Annex H
(informative)

Examples of interactions between pre-travel activity and travel times

H.1 Example of interactions calculations

Figure H.1 shows a worked example using the results of evacuation time calculations calculated with a computer simulation method (GridFlow [16]), for various occupancy levels of a simple square retail space (42,4 m on each side, direct travel distance, 30 m) with four available exits. The model treats each occupant as an individual and walking speeds depend upon occupant density. For these calculations, a design population of 900 and the pre-travel activity time distribution obtained in the Sprucefield monitored evacuation (see Reference [5]) are used. In this case, the first occupants began to move almost immediately after the general alarm was sounded, so that the pre-travel activity time of the first few occupants to move is only a few seconds. Walking distances were computed for each occupant and for a walking speed distribution with a mean of 1,2 m/s (standard deviation, 0,2 m/s; minimum, 0,3 m/s).

Figure H.1 shows a number of features of an evacuation for different occupant populations. Key item 7, the Nelson-Mowrer line [11], shows the time calculated for the occupant population to flow out of the enclosure, assuming the available exits are used to maximum flow capacity from the moment the alarm is sounded. This represents the minimum possible times required to evacuate the population ignoring the pre-travel activity and walking time components. The two horizontal broken lines, key items 3 and 2, respectively, show the theoretical 95th and 99th percentile pre-travel activity times of 95 s and 114 s, which are constant for the given distribution. The 99th percentile line plus a figure for average walking time of 13 s provides a presentation time of approximately 127 s, shown as key item 1, which represents the minimum time required to evacuate assuming unimpeded movement.



Key

X	population of space	4	last out
Y	time, expressed in seconds	5	99 %
1	99th percentile presentation	6	95 %
2	99th percentile PTAT	7	Nelson-Mowrer line
3	95th percentile PTAT		

Figure H.1 — Phases of evacuation times for different populations in a square prescriptively designed retail enclosure with an area of 18 000 m^2 calculated using GridFlow with the Sprucefield pre-travel activity time distribution

Key items 6, 5 and 4, respectively, show the times required for 95 % and 99 % of the population and the last out from full computer simulations for all individual occupants, taking into account all interactions (including impeded movement) for different populations (average of 10 simulations for each point). The results show that at the design population of 900, the minimum flow time for the occupant population exceeds the 99 % pre-travel activity and presentation time limits by a considerable margin of 95 s and 82 s.

The separation between the Nelson and Mowrer time and the actual 99 % evacuation time provides an approximate estimate of the time to queue formation of 20 s, which represents the presentation time of the first few occupants. The pre-travel activity times and walking times of the remainder of the population after the first 20 s have no further effect on the evacuation time of 99 % of occupants, which is determined simply by the maximum flow time required for the occupant population. This clearly indicates that, at the high (design) occupant densities, once the first few occupants begin to move, the evacuation is limited by (and therefore determined by) the physical dimensions of the exits plus a small period for the time required for queues to form, i.e. as given by Equation (H.2).

When the occupant numbers are less than approximately one-third of the design number, then the evacuation time depends on the pre-travel activity time of the last occupants to start to leave, i.e., as given by Equation (H.1).

H.2 Simple method for calculating the effects of interactions between pre-travel activity time and travel time distributions

The analysis presented in Clause H.1. demonstrates that, in practice, it is possible to reduce the complex interactions between pre-travel activity time and travel time distributions to simple calculations without incurring a significant error.

This can be achieved for any building enclosure by considering two simple boundary cases; see References [16], [17], [48].

a) The enclosure is sparsely populated with a population density of less than one-third the design population.

b) The enclosure contains the maximum design population.

For the first case, the evacuation time depends upon the pre-travel activity 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, $\Delta t_{\text{evac},1}$, is then given by Equation (H.1):

$$\Delta t_{\text{evac},1} = \Delta t_{\text{pre(99th percentile)}} + \Delta t_{\text{trav (walking)}} \tag{H.1}$$

where

$\Delta t_{\text{pre(99th percentile)}}$	is the time from alarm to movement of the 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 can use the maximum direct travel distance for the enclosure).

For the second case, the evacuation time, $\Delta t_{\text{evac},2}$, depends upon the pre-travel activity and walking time of the first few occupants plus the flow time of the exits, which is given by Equation (H.2):

$$\Delta t_{\text{evac},2} = \Delta t_{\text{pre(1st percentile)}} + \Delta t_{\text{trav (walking)}} + \Delta t_{\text{trav (flow)}} \tag{H.2}$$

where

$\Delta t_{\text{trav (flow)}}$	is the time for the total occupant population to flow though available exits;

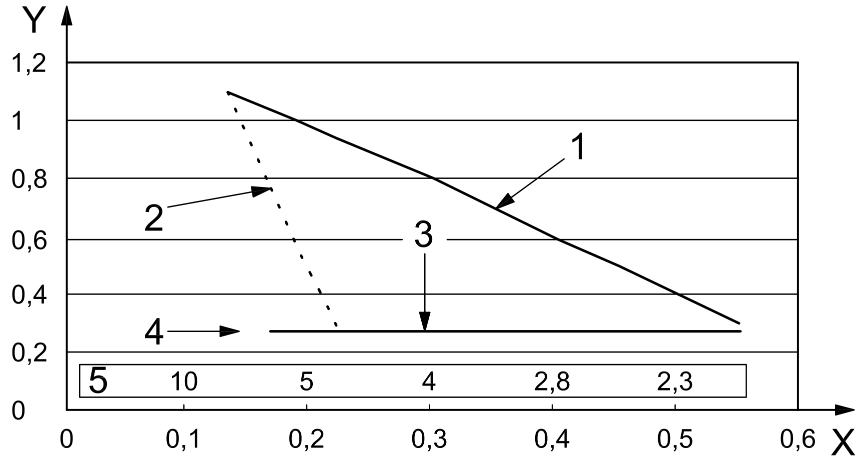
$\Delta t_{pre(1st\ percentile)}$ is the time from alarm movement of the first few occupants (from Table E.2.).

The longest time may be used for design purposes and, in most scenarios, the second case represents the longest required escape times. Default figures for the 1st and the 99th percentile pre-travel activity times are presented in Table E.2.

Annex I
(informative)

Effects of smoke on walking speed

Figure I.1 shows the effects of exposure to non-irritant smoke and irritant wood smoke on walking speed and walking speed in darkness derived from the work of Jin [25]. Also shown is the smoke density at which 30 % of people turn back rather than enter; see References [22] and [8].



Key

X smoke, optical density per metre

Y walking speed, metres per second

1 non-irritant smoke

2 irritant wood smoke

3 30 % of people turn back rather than enter

4 walking speed in darkness

5 visibility, expressed in metres

Figure I.1 — Walking speeds in non-irritant and irritant smoke

The relationship between walking speed in non-irritant smoke, v_{NI}, and in irritant smoke, v_I, expressed in metres per second, and the smoke optical density, ρ_{OD}, expressed as reciprocal metres, is given by Equations (I.1) and (I.2), respectively:

$$v_{NI} = 1{,}36 - 1{,}9\rho_{OD} \qquad \text{(I.1)}$$

$$v_I = 2{,}27 - 9{,}0\rho_{OD} \qquad \text{(I.2)}$$

Table I.1 shows the main criteria used to derive tenability limits. Based upon the consideration that smoke from fires in buildings or vehicles has been found to be irritant, a design tenability limit of $\rho_{OD} = 0{,}2\ m^{-1}$ is recommended for small enclosures such as dwellings. A proportion of people might not enter smoke at this density and, if they do, their movement speed is likely to be reduced to that in darkness. For larger enclosures, such as those in public buildings, a design tenability limit of $\rho_{OD} = 0{,}08 m^{-1}$ is proposed, so that occupants can orientate themselves and find exits.

Table I.1 — Smoke tenability limits

Smoke			Approximate visibility (diffuse illumination)	Reported effects
Type	Density ρ_{OD} m^{-1}	Extinction coefficient		
None	—	—	Unaffected	Walking speed 1,2 m/s
Non-irritant	0,5	1,15	2 m	Walking speed 0,3 m/s
Irritant	0,2	0,5	reduced	Walking speed 0,3 m/s
Mixed	0,33	0,76	approx. 3 m	30 % people turn back rather than enter
Suggested tenability limits: — for buildings with small enclosures and travel distances: ρ_{OD} = 0,2 m^{-1} (visibility of 5 m); — for buildings with large enclosures and travel distances: ρ_{OD} = 0,08 m^{-1} (visibility of 10 m).				

These limits are intended to enable safe escape of the majority of building occupants. Some occupants might attempt to escape through even dense smoke in some situations. Also of importance is the tolerability of the smoke in terms of toxic gases and heat.

It is considered that exposure to irritant gases above certain concentrations in smoke severely impairs and even prevents escape. For the majority of flaming fires, it is considered that the concentrations of mixed smoke irritants are below this level provided that the smoke optical density does not exceed ρ_{OD} = 0,2 m^{-1}. Exceptions can be smouldering fires, for which the organic irritant yields tend to be high, and fires involving fuels giving off significant yields of inorganic acid gases (HCl, HBr, HF, SO_2, NO_x). Guidance on estimation of irritancy for such fires is given in ISO 13571 and in Purser [24].

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