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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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
$t_{\text{trav (walking)}}$	walking time during travel time
$t_{\text{trav (flow)}}$	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.

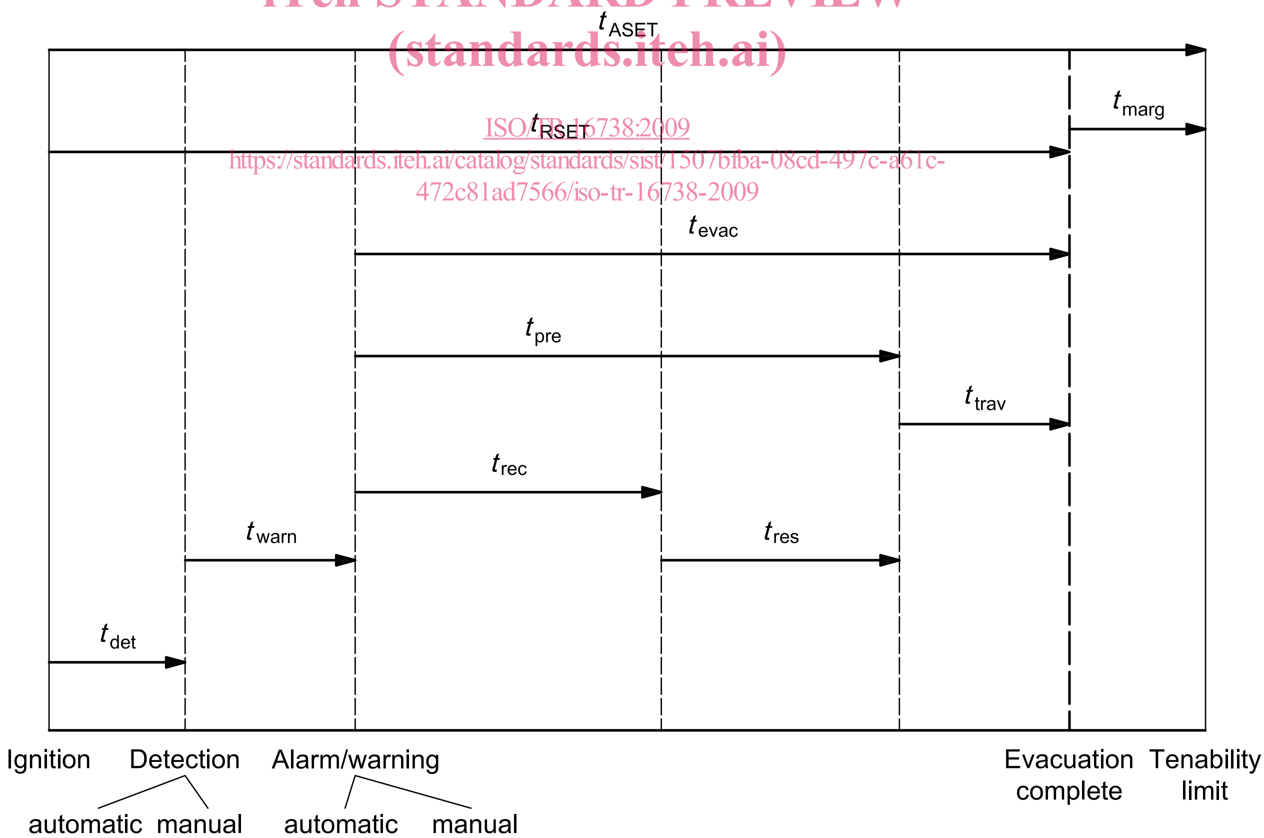

Figure 1 — Simplified diagram of processes in required safe-escape time compared to available safe-escape time

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):

$$t_{\mathrm{marg}} = t_{\mathrm{ASET}} - t_{\mathrm{RSET}} \tag{1}$$

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):

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

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.