TECHNICAL
REPORT

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Fire safety engineering —

Part 8:
Life safety — Occupant behaviour, location and condition

Ingénierie de la sécurité contre l'incendie —

Partie 8: Sécurité des personnes — Comportement des occupants, emplacement et état physique

Reference number
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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of ISO technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, 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).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 13387-8, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92*, Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

It is one of eight parts which outlines important aspects which need to be considered in making a fundamental approach to the provision of fire safety in buildings. The approach ignores any constraints which may apply as a consequence of regulations or codes; following the approach will not, therefore, necessarily mean compliance with national regulations.

ISO/TR 13387 consists of the following parts, under the general title *Fire safety engineering*:

— *Part 1: Application of fire performance concepts to design objectives*

— *Part 2: Design fire scenarios and design fires*

— *Part 3: Assessment and verification of mathematical fire models*

— *Part 4: Initiation and development of fire and generation of fire effluents*

— *Part 5: Movement of fire effluents*

— *Part 6: Structural response and fire spread beyond the enclosure of origin*

— *Part 7: Detection, activation and suppression*

— *Part 8: Life safety — Occupant behaviour, location and condition*

Annexes A and B of this part of ISO 13387 are for information only.

Introduction

This part of ISO 13387 provides guidance on engineering methods currently available for the evaluation of occupant behaviour, particularly escape behaviour, during a fire emergency and for the evaluation of occupant condition, particularly in relation to exposure to fire effluent and heat. These are reported as two major evaluation outputs: occupant location and condition.

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

a) the building design and emergency life safety management strategy;

b) the occupant characteristics;

c) the fire simulation dynamics;

d) the 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; the interaction of all these features with the developing fire scenario and provisions for emergency intervention (fire brigade and rescue facilities). Key aspects on theses inputs are described in annexes A and B.

This part of ISO 13387 is intended for use together with the other parts of ISO 13387. These latter provide the input information for this part of ISO 13387 but take up the output from this document.

Clause 4 of this document outlines the information flow system for subsystem 5 (SS5), i.e. life safety, the life safety engineering flow chart, and the interactions between this part and the other parts of ISO 13387.

Clause 5 describes the processes involved in the evaluation of parameters relating to location and condition of building occupants exposed to a fire with respect to time. Occupant location and condition are outputs necessary for the global information bus to enable a determination of whether the life safety objectives of the design have been achieved. Life safety objectives and their evaluation is described in ISO/TR 13387-1.

Clause 6 is a discussion of the engineering methods available for the evaluations.

Further bibliography can be found in the other parts of ISO 13387.

Fire safety engineering —

Part 8:
Life safety — Occupant behaviour, location and condition

1 Scope

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

This part of ISO 13387 is intended to provide guidance to designers, regulators and fire safety professionals on the engineering methods available to evaluate the location and condition of the occupants of a building exposed to a fire.

This part of ISO 13387 addresses the assumptions that underlie the basic principles of designing for life safety and provides guidance on the processes, assessments and calculations necessary to determine the location and condition of the occupants of the building, with respect to time.

This part of ISO 13387 also provides a framework for reviewing the suitability of an engineering method for assessing the life safety potential of a building for its occupants.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO/TR 13387. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO/TR 13387 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO/TR 13387-1, *Fire safety engineering — Part 1: Application of fire performance concepts to design objectives.*

ISO/TR 13387-2, *Fire safety engineering — Part 2: Design fire scenarios and design fires.*

ISO/TR 13387-3, *Fire safety engineering — Part 3: Assessment and verification of mathematical fire models.*

ISO/TR 13387-4, *Fire safety engineering — Part 4: Initiation and development of fire and generation of fire effluents.*

ISO/TR 13387-5, *Fire safety engineering — Part 5: Movement of fire effluents.*

ISO/TR 13387-6, *Fire safety engineering — Part 6: Structural response and fire spread beyond the enclosure of origin.*

ISO/TR 13387-7, *Fire safety engineering — Part 7: Detection, activation and suppression.*

ISO 13571:—[1], *Fire hazard analysis — Life-threatening components of fire*.

ISO 13943, *Fire safety — Vocabulary*.

3 Terms and definitions

For the purposes of this part of ISO 13387, the definitions given in ISO 13943, ISO/TR 13387-1 and the following apply:

3.1
asphyxiant
toxicant causing hypoxia, resulting in central nervous system depression with loss of consciousness and ultimately death

3.2
defend in place
life safety strategy in which occupants are encouraged to remain in their current location rather than to attempt escape during a fire

3.3
evacuation process
process which enables occupants of a building to reach a place of safety (where appropriate), consisting of pre-movement and movement processes

3.4
fractional effective concentration
FEC
ratio of the concentration of an irritant to that expected to produce a given effect on an exposed subject; when not used with reference to a specific irritant, this term represents the summation of FECs for all irritants in a combustion atmosphere

3.5
fractional effective dose
FED
ratio of the concentration of the asphyxiant toxicant to that concentration of the asphyxiant expected to produce a given effect on an exposed subject; when not used with reference to a specific asphyxiant, this term represents the summation of FEDs for all asphyxiants in a combustion atmosphere

3.6
incapacitation
state of physical inability to accomplish a specific task, for example safe escape from a fire

3.7
irritation,
<sensory or upper respiratory> the stimulation of nerve receptors in the eyes, nose, mouth throat and respiratory tract, causing varying degrees of discomfort and pain along with the initiation of a range of physiological responses (including reflex eye closure, tear production, coughing, bronchoconstriction)

3.8
movement processes
process which enables occupants of a building to reach a place of safety once they have begun to evacuate, where appropriate

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[1] To be published.

3.9
pre-movement process
process occurring during which the occupants recognize and respond to the alarm or cue of fire, where appropriate, before they begin to evacuate

NOTE This process can be divided into two components, “recognition” and “response” [see also **defend in place** (3.2) and **movement processes** (3.8)].

3.10
recognition
process occurring during the period after an alarm or cue has been given but before occupants of a building begin to respond

NOTE The recognition time ends when the occupants realize that there is a need to respond.

3.11
response
process occurring after occupants recognize the alarms or cues and begin to respond to them, but where appropriate, before they begin to evacuate

3.12
impaired escape capability
effects on willingness and efficiency of escape actions, which may delay, slow or prevent evacuation

4 Design subsystem 5 of the total fire safety design system

4.1 General

An ideal fire safety design would ensure that building occupants are able to reach a place of safety without ever coming into contact with or even being aware of fire effluent and/or heat. This should be the main design criterion for the safety of the majority of occupants in multi-compartment buildings. However, there will inevitably be some potential scenarios when some occupants will become aware of or be exposed to fire effluent, particularly when the occupants are in the enclosure of fire origin. This may vary between slight smoke contamination, common in many accidental fires, to life threatening exposures such as in major fire disasters. For all of these types of scenarios, it is important to be able to assess the likely effects of such exposures, either as part of the main design or as part of a risk assessment.

In most systems of fire safety regulation measures are taken to ensure the life safety of the occupants by prevention of ignition, prevention of 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 the work of ISO/TC 92/SC 4 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 evaluation 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 some prescriptive parameters may need to be observed in any assessment of the life safety provisions within a building.

4.2 Information system

In the framework document the total fire safety design is illustrated by a global information bus which has three layers: global information, subsystem evaluations and subsystem processes. The information system for this subsystem is illustrated in Figure 1.

4.3 Function of subsystem 5

The function of subsystem 5 is to determine the location and condition of the occupants with respect to time. The analysis necessary is illustrated in the flow chart, Figure 2.

The upper part of the flow chart shows the input data from the relevant sections of the global information system and the framework document ISO/TR 13387-1.

The next part identifies the processes necessary for the evaluations.

The next part shows the evaluation of occupant condition and location, which are output to the global information system at the bottom for further processing.

ISO TC 92/SC 4 FIRE SAFETY ENGINEERING BUS SYSTEM

Subsystem 5 (SS5) — Life safety — Occupant behaviour, location and condition

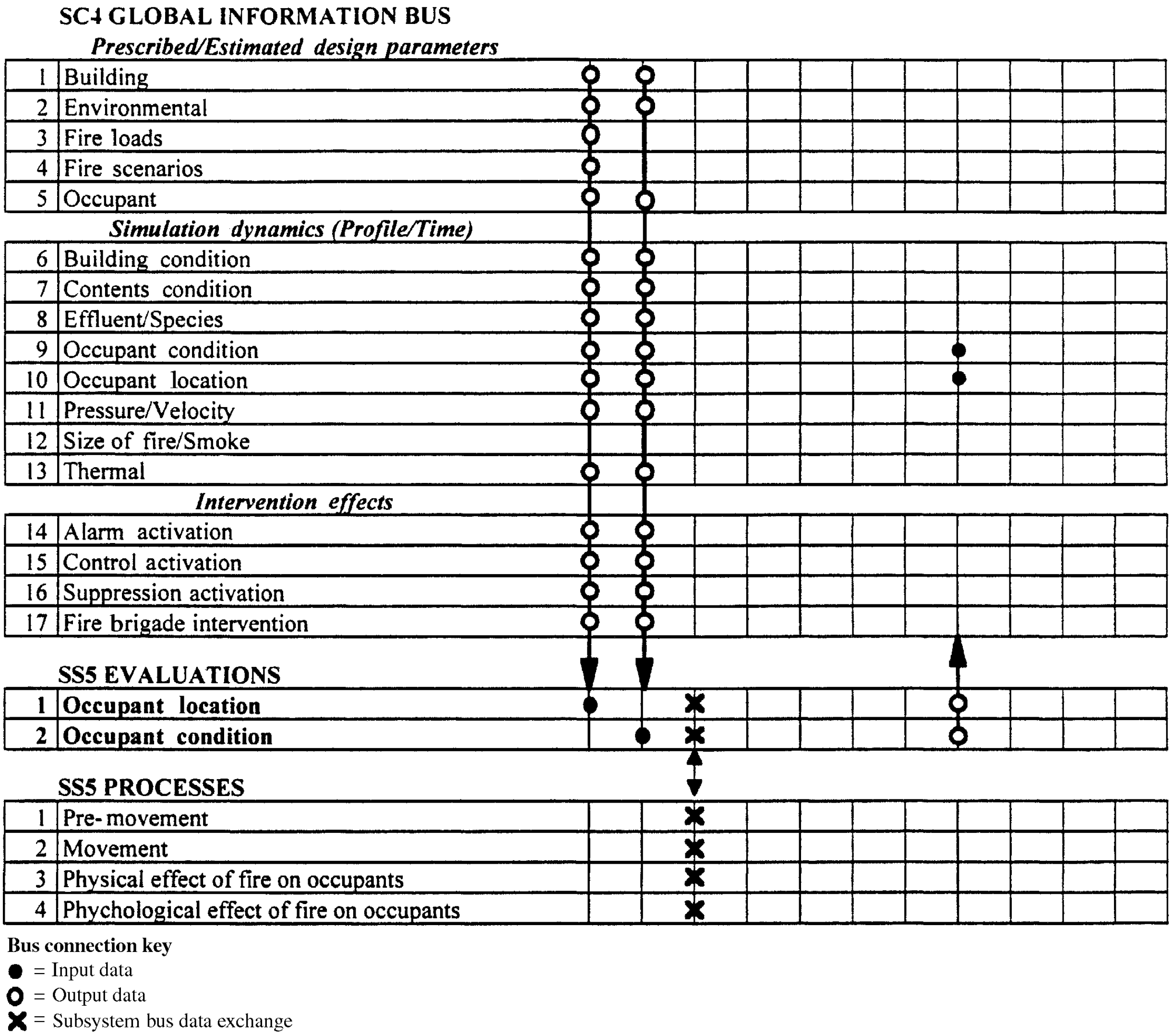

Figure 1 — Illustration of the global information, evaluation and process buses for SS5

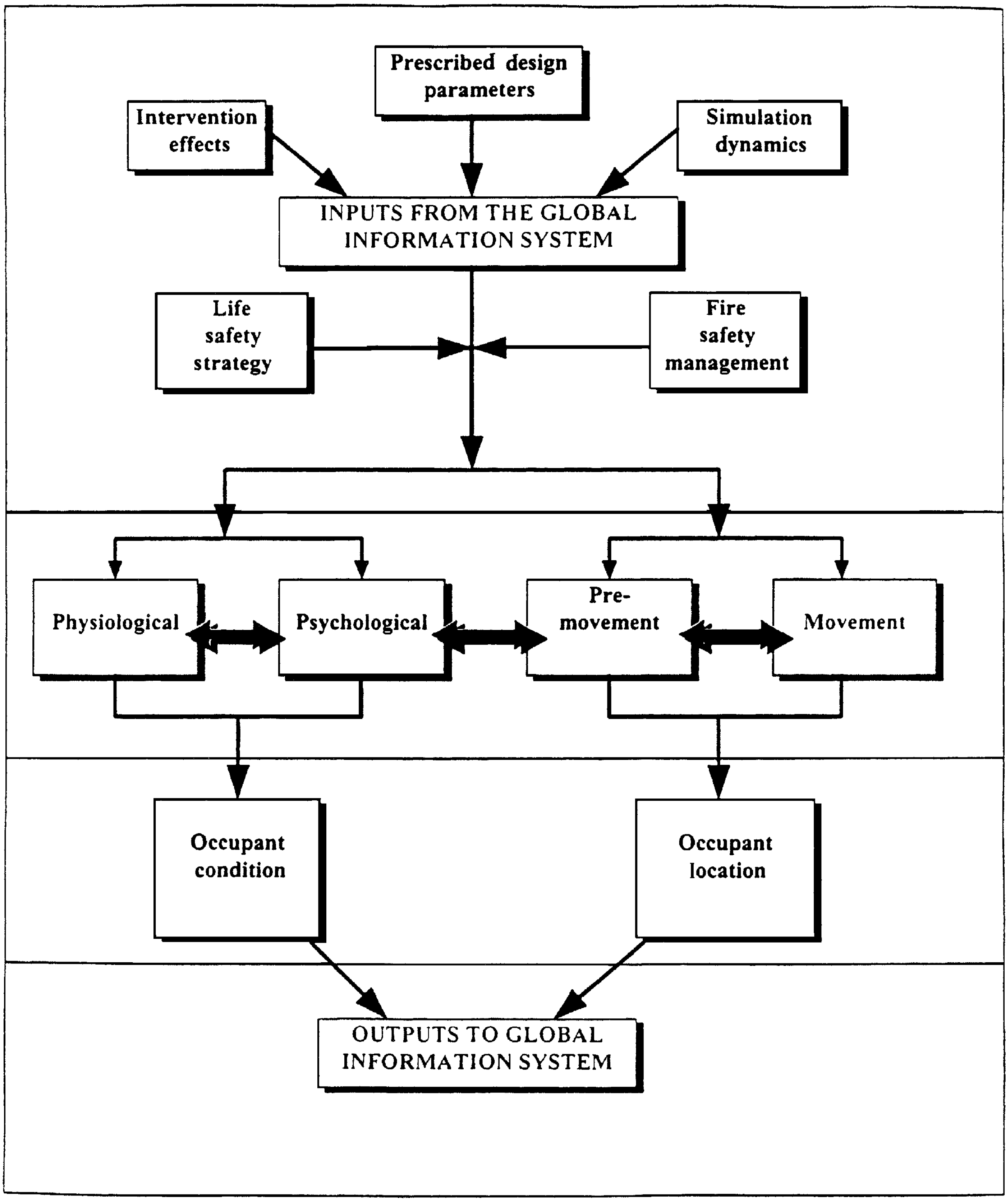

Figure 2 — Life safety engineering flow chart

5 Subsystem 5 (SS5) life safety: evaluations

5.1 General

The purpose of any life safety strategy is to ensure that, in the event of a fire the occupants will be able to leave the building, evacuate to a designated space within a building, or remain *in situ* (as appropriate), without being exposed to untenable conditions. An ideal fire safety design would ensure that building occupants are able to reach a place of safety without ever coming into contact with or even being aware of fire effluent and/or heat. This should be the main design criterion for multi-compartment buildings. However, there will inevitably be some potential scenarios when some occupants will become aware of or be exposed to fire effluent, particularly when the occupants are in the enclosure of fire origin. This may vary between slight smoke contamination, common in many accidental fires, to life threatening exposures such as in major fire disasters. For all of these types of scenarios, it is important to be able to assess the likely effects of such exposures, either as part of the main design or as part of a risk assessment. A single acceptable criterion of no permitted exposure could impose serious constraints on the design. This part of ISO 13387 allows for a more flexible approach to fire safety engineering by providing a basis for estimating levels of exposure that would not be expected to seriously impair escape or impair health.

Whilst the processes for determining the occupant location and the occupant condition can be dealt with as discreet issues, there is in reality significant interaction between them. Guidance is given in this clause on the processes involved and on these potential interactions. The life safety strategy developed for a building is an integral element of the design philosophy detailed in the framework document ISO/TR 13387-1.

The strategy may require evacuation of the occupants, by either simultaneous or phased procedures, evacuation to a place of safety within a building or that occupants remain in a place of safety. The strategy should not normally rely on direct assistance to the occupants, except for special cases such as evacuation of people with disabilities.

In order to determine the adequacy of fire engineering design of buildings in terms of life safety, it is necessary to evaluate over time, the impact of the design fire scenario on the occupants in terms of their:

a) location;

b) condition.

The location of occupants within a building, at any one time, and the way occupant location changes with time during normal use and emergency situations depends upon the interaction of a variety of parameters related to the characteristics of the building and the occupants, the fire safety management system adopted and the developing fire scenario. The condition of the occupants depends upon their psychological and physiological state before the fire and the subsequent effects of the developing emergency including any exposure to fire effluent and heat.

As a result of the very large number of variables involved, difficulties in their identification and quantification and difficulties in predicting interactions between them, not even the most complex and sophisticated behavioural and physiological model can hope to provide a full representation of all the possible processes and outcomes of any scenario. Some methods are designed to address only one or a few of these processes, while others claim to provide a more global approach. It is therefore important when evaluating any particular building design to take account of all the parameters which may affect the life safety of occupants and chose appropriate evaluation methodology. The different methods available are reviewed in clause 6. It is essential that a design review is first undertaken before the application of any of the engineering methods discussed. The following subclauses introduce the various inputs and parameters to be considered and discuss aspects that are essential to the evaluation process.

5.2 Inputs required from the global information bus

As shown in Figure 2 there are essentially four categories of information required to determine the condition and location of occupants:

a) the building characteristics and fire safety management strategy;

b) the occupant characteristics;

c) the fire simulation dynamics;

d) intervention effects.

5.2.1 The building characteristics and fire safety management strategy

The first major input to the life safety evaluation processes comprises 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, as follows:

- layout and geometry (including size, building height, ceiling height, layout, complexity, compartment, 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 (for example by break-glass and key only, by crash bar), use during normal flows in building, final exits (number distribution related to characterization data), etc.];
- building use [including general building/occupancy type (for example office, department store, theatre, etc.), layout and functions/uses in particular locations within the building which may 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 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 fire brigade, emergency lighting, wayfinding system, 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);
- signs 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 (for example wind and internal air pressurization on door opening force, evacuations in wet, hot or cold conditions, dress requirements, effect of snow on exits).

Guidance on these parameters is given in A.1.

5.2.2 The occupant characteristics

The second major input to 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 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 sight of or exposure to fire effluent or heat.

Occupant characteristics to be considered include:

a) population numbers and density: expected numbers in each occupied space including seasonal variations;

b) familiarity with the building: depends on factors such as occupancy type, frequency of visits and participation in emergency evacuations;

c) distribution and activities;

d) alertness: depends on factors such as activities, time of day, sleeping or awake;

e) mobility: depends on factors such as age and any disabilities;

f) physical and mental ability;

g) social affiliation: extent to which occupants present as individuals or in groups such as family groups, groups of friends, etc.;

h) role and responsibility: includes categories such as member of the public, manager, floor warden, etc.;

i) location: location in building relative to escape routes, etc.;

j) commitment: extent of commitment to activities engaged in before the fire;

k) focal point: point where occupant attention is directed, such as the stage in a theatre or a counter in a shop;

l) responsiveness: extent to which occupant is likely to respond to alarms, etc.;

m) occupant condition: as determined by the analysis of occupant condition.

Guidance on these parameters is given in A.2.

5.2.3 The fire simulation dynamics

The third major input to 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 life safety 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.

The following specific factors need to be considered:

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 would become aware of the situation, and how they would 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, activation of suppression and smoke control systems.

   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 known 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 to 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 need to be reported.

5.2.4 Intervention effects

Circumstances may 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. Further guidance in given in annex B.

5.3 Occupant location

At the moment the fire starts, the building will contain a certain number of occupants dispersed in a particular pattern depending principally upon the season of the year and time of day or upon any particular planned events taking place as well as the variety of activities in which the occupants are engaged. The subsequent behaviour of the occupants and the time required for them to react will depend upon the interactions of the various input parameters described and the occupant response processes.

When the first cues to the occurrence of a fire become available to the occupants of different parts of a building or when an alarm is given, the occupants engage in a variety of behaviours (see references (see references [1], [2] and [3]). These behaviours require certain times for their execution so that the location of occupants can be assessed on a time basis. The behaviours involved in the evacuation process have been classified into two broad processes in this document, the pre-movement process occurring before the physical evacuation begins and the movement process during which occupant evacuate to a place of safety (if appropriate). Each of these have sub-categories which need to be identified and addressed in a design review and incorporated into a performance assessment. Occupant response behaviours and movements will vary according to a number of variables. The pattern and timing of the overlapping phases of behaviour and movement also vary with the type of occupancy, architectural setting, fire growth scenario and other factors. Different assessment methods and models handle these variables to different extents.

5.3.1 Pre-movement processes

During an evacuation, the pre-movement processes take place after an alarm of cue has become evident, but before the occupants of the building begin to evacuate (where evacuation is appropriate). These processes may be sub-divided into two components, “recognition” and “response”.

There is a lack of reliable data upon which to base accurate predictions of pre-movement time, although it may comprise a significant part of the total time required for escape (see references [3], [4] and [5]). Pre-movement time varies between individuals within an enclosure and between groups in different enclosures within a building. The following procedure has been developed which may assist in assessing the pre-movement time of occupants.

The two components of pre-movement time have the following characteristics.

a) Recognition

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

During the recognition period occupants continue with the activities engaged in before the alarm of cue, such as working, shopping or sitting. The length of the recognition period can be extremely variable, depending upon factors such as the types of building, the nature of the occupants and the building alarm and management system (see references [1], [2], [3], [4] and [5]).

In single enclosure buildings that are well managed the recognition period is likely to be short. In multi-enclosure buildings where occupants may be remote from the fire, especially those with a sleeping risk such as hotels, residential homes and hostels, the recognition times may vary considerably (see references [1], [2], [3], [4] and [5]). The recognition time ends when the occupants have accepted that there is a need to respond.

b) Response

This consists of a period after occupants recognize the alarms or cues, and begin to respond to them, but before they begin to evacuate (where necessary). As with the recognition period this may range from a few seconds to many minutes, depending upon the circumstances (see references [1], [2], [3], [4] and [5]).

Examples of activities undertaken during the response time include:

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

2) stopping machinery/production processes or securing money and other risks;

3) seeking and gathering together children and other family members;

4) fighting the fire;

5) the time involved in determining the appropriate exit route (i.e. “wayfinding”); and

6) the time involved in other activities not fully contributing to effective evacuation where necessary (for example acting on incorrect or misleading information);

7) alerting others.

Pre-movement times may 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-movement times depends upon a range of factors including the occupants 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-movement times is likely to be narrow (everyone starting to move at about the same time), whereas in a multi-enclosure setting such as a hotel there is likely to be a wide distribution of pre-movement times. Those in the enclosure of fire origin may complete the pre-movement process before those in other enclosures even become aware of the fire.

The provision of reliable data on the pre-movement times to be 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 no comprehensive or reliable database of pre-movement times is currently available, this is an active area of research (see references [2], [3], [4] and [5]).

5.3.1.1 Pre-movement recognition time

During the recognition process each occupant is engaged in their normal activities, but is receiving and processing cues about the developing emergency situation. For each individual this process ends when they decide to take some action in response to the emergency cues received. The evaluation of location therefore starts with the distribution of occupants throughout the building at the start of the recognition process. The first evaluation is to estimate the time that the recognition process ends for each occupant. The recognition time will vary between different individual occupants in any one enclosure within the building, and for groups of occupants in different enclosures. For simple evaluations a single figure such as the average or slowest recognition time may be taken for each group of occupants. For more complex evaluations recognition times may be assigned to each individual occupant. A range of factors can be taken into account in order to estimate recognition time. The principle ones are as follows:

5.3.1.1.1 Inputs — at each time increment where appropriate

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: 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 (for example from management or other occupants);
   6) active protection status.

5.3.1.1.2 Output

Occupant location:

— recognition time for each occupant and distribution of recognition times for groups in each enclosure.

5.3.1.2 Pre-movement response time

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 will have decided either to remain in the same enclosure or to begin evacuation. For simple evaluations a single figure such as the average or slowest response time may be taken for each group of occupants. For more complex evaluations response times may be assigned to each individual occupant. A range of factors can be taken into account in order to estimate response time. The principle ones are as follows:

5.3.1.2.1 Inputs — at each time increment where appropriate

a) Building parameters
   1) occupancy type;
   2) floor plans, layout and dimensions;
   3) contents;
   4) warning system;
   5) fire safety management emergency procedures;
   6) signs;
   7) lighting;
   8) location of exits and complexity of enclosure layout.

b) Occupant status:
   1) occupant numbers and starting location;
   2) occupant characteristics: age and health status;

  3) occupant activities before emergency;
  4) family or group relationships;
  5) 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 (for example from management or other occupants);
  6) active protection status.

5.3.1.2.2 Output

Occupant location:

response time for each occupant and distribution of response times for groups in each enclosure.

5.3.1.3 Total pre-movement time

For each occupant the time taken from the first emergency cues becoming available and the start of evacuation (where appropriate) is the pre-movement time. This may be estimated as the sum of the recognition and response times for each occupant or group of occupants in each enclosure within the building.

5.3.2 Movement processes

Movement processes are those which enable occupants to reach a place of safety once they have begun to evacuate (where evacuation is appropriate).

Analysis of movement processes is directed at estimating the times required for evacuation of occupants from the various enclosures within the building and times for passage through escape routes. In any particular scenario the patterns of evacuation flow that are likely to take place under emergency conditions will depend upon a number of factors, such as the building layout, the familiarity of the occupants with the building, the location of the fire and the fire safety management procedures (see references [1], [2], [3], [4] and [5]). As with all evacuation parameters it is possible to make simple or more complex simulations of movement flows, depending upon the information available, the models used and the complexity of the situation. Using appropriate methods it is possible to predict evacuation patterns with reasonable accuracy (see references [6] and [7]). These predictable flow conditions enable egress arrangements to be tested and enable prediction of times for the movement of the occupants to exits from each enclosure and from the whole building.

5.3.2.1 Inputs for evaluation of movement time

The most important considerations are the following.

a) Numbers and distribution of occupants immediately before evacuation.

  In particular it is necessary to establish the occupant capacity of each enclosure. It is recommended that one of the evacuation cases to be considered for design purposes is that involving the maximum anticipated occupancy. Where no information is available on actual occupancy levels, an estimate should be based on the type of occupancy and the floor areas. Advice on occupancy figures is available from a number of sources (see reference [5]). The starting point for the egress calculation is the location of the building occupants immediately after the pre-movement process.

b) Occupant status including age, physical and mental capacity, family or group relationships, cultural attributes, status (for example: customer, resident, manager, security personnel, etc.). Occupant mix in terms of these categories may be important.

c) Exit choice.

An important early determinant of evacuation flow densities is the choice of exits and escape routes likely to be exercised by groups of occupants. This depends upon a number of factors including the fire scenario, the familiarity of the occupants with the building, the occupancy type and the fire safety management system (see references [1] and [2]).

d) Occupant density.

The travel speed of occupants towards exits, through passageways and down (or up) stairs depends principally upon occupant characteristics such as age, gender, agility and grouping (family groups tend to move at the speed of the slowest member) and also density which changes throughout the movement period (see references [6] and [7]).

e) Travel distance and travel times.

Travel distances and hence the travel times for individual occupants to reach their chosen exits constitute another parameter affecting movement time. Travel distances are particularly important as a factor in movement times in more sparsely occupied enclosures, where the occupant flow at exits may not reach maximum capacity, so that queue formation may not occur; also in situations where large groups of occupants may be located some distance from an exit. In crowded enclosures it is likely that queuing will occur at some exits as they reach maximum flow capacity so that one factor in evacuation time is the time to queue formation (see reference [7]). Other determinants of travel speed are whether the route is level, ramped or a stair, the merger of two or more routes and the occupant characteristics (see references [6], [7], [8] and [9]).

Travel distances in enclosures as used for calculating movement times are the actual distances covered by individual occupants from their location at the end of the pre-movement period to the enclosure exits used. Estimates of travel distance should take into account the design fire scenario. Also important are any obstacles within the enclosure such as partitions, displays of goods, etc.

f) Flows through doorways, corridors and stairs.

Once a flow of occupants is established at enclosure exits the evacuation through the remainder of the escape route can be estimated. Reasonably good empirical data exist to enable the flow capacity of the main elements of escape routes (doorways, corridors and stairs) to be calculated (see references [6] and [7]). Circulation spaces and egress routes should be designed to ensure that people are accommodated with reasonable comfort. Effort should be made at the design stage to achieve simplicity in all access and egress arrangements

Although closely packed conditions may be acceptable in non-emergency conditions, if delays or queues occur during evacuation a closely-packed slow-moving crowd could become anxious, which may result in crushing and related injuries.

In determining the width available for evacuation and assessment or measurement of the exit route it should be borne in mind that persons moving along a corridor or stairway produce an effective boundary layer of clearance between themselves and walls, handrails and other obstacles. The width of the boundary layer(s) needs to be taken into account to determine the effective width available (see reference [6]). Calculation of travel speed should take account of any merging flows (see reference [7]).

Movement speeds depend to some extent on occupant mobility (see references [8] and [9]). Flows may be affected by occupants with walking aids or wheelchairs.

To facilitate assessment, the egress path under consideration may be divided into spaces (such as rooms, lobbies, corridors and stairways) and their interconnecting doorways. The procedure must be repeated for each space on the exit path for a number of time steps until the evacuation has been completed.

To enable the movement time to be assessed the information needed and would typically include for each occupied enclosure:

a) tenability in exit paths;

b) number of occupants likely to use each exit path;

c) occupant condition;

d) number of exits which may be available;

e) appropriate subdivision of escape paths into zones and sectors;

f) the evacuation strategy;

g) occupant density at exits;

h) maximum flow capacity of exits and escape routes;

i) occupant density in escape routes;

j) merging flows in escape routes;

k) occupant movement velocity.

When carrying out a detailed analysis it will generally be necessary to derive the following information for each time step:

a) nature and number of occupants within each enclosure;

b) rate of flow (if any) into each enclosure;

c) rate of arrival at the exit from each enclosures;

d) rate of flow out of flow out of the enclosure.

In highly populated buildings the available exit width may dominate the evaluations and considerations of the distance occupants have to travel and their movement speeds may become secondary.

5.3.2.2 Output

The output of the movement process is the location of all building occupants with time from the time the fire starts to the time when occupants have evacuated to a place of safety (if required).

5.4 Occupant condition

5.4.1 General

The parameters which need to be considered with respect to occupant condition for all fire scenarios are the appearance of fire (i.e. being able to see smoke or flames), visual obscuration by smoke, smoke irritancy, the effects of asphyxiant gases and of radiant and convected heat.

Throughout the time course of the fire the condition of the occupants should be evaluated with respect to any exposure to fire effluent or heat. For some hazards (irritants, smoke density and radiant heat) the most important parameter is the concentration or intensity of the hazard (see references [10] and ISO 13571). For others (asphyxiant gases and convected heat) the most important parameter is the exposure dose (see references [10], [11] and [12]) and ISO 13571). Therefore, in order to evaluate life safety during a fire it is necessary to obtain continuous information on the extent of the fire and fire effluent and to estimate their effects on the occupants.

The main evaluations that need to be performed are the psychological and physiological condition of the occupants. The main considerations are tenability of all occupied spaces and the tenability of escape routes from occupied spaces.

With regard to psychological aspects in relation to occupied spaces it is necessary to determine whether occupants are likely to feel sufficiently secure to remain in place or whether they feel sufficiently threatened to attempt to leave. If they wish to leave it is necessary to determine whether the conditions in the escape routes are sufficiently good to enable occupants to decide to escape. These considerations will depend partly on perceived hazard, such as being able to see flames and partly on physiological considerations, such as discomfort resulting from exposure to irritant smoke.

With regard to physiological aspects it is also necessary to determine the extent to which occupants are physically capable of escaping. This involves effects which may render escape attempts slower or less efficient, such as exposure to optically dense or irritant smoke. It also involves determination of the point where occupants are likely to become incapacitated, so that they are unable to escape unaided. An example of incapacitation would be loss of consciousness due to carbon monoxide intoxication. It may also be important as part of a risk assessment to estimate possible long term adverse health effects of an exposure and when an exposure is likely to prove lethal.

The psychological and physiological effects of exposure to toxic smoke and heat in fires result in varying degrees of effects on escape behaviour or incapacitation which may also lead to death or permanent injury.

Behaviour modifying or incapacitating effects include:

a) Effects of seeing smoke or flames including:

    1) fear of approaching smoke or heat-logged areas or escape routes;

    2) fear of fire or smoke in an occupied compartment as a stimulus to escape; or

    3) attraction towards fire in an occupied compartment (friendly fire syndrome) to observe or tackle fire (see references [12] and [13]).

b) Impaired vision resulting from the optical opacity of smoke and from the painful effects of irritant smoke products and heat on the eyes.

c) Respiratory tract pain and breathing difficulties or even respiratory tract injury resulting from the inhalation of irritant smoke which may be very hot. In extreme cases this can lead to collapse within a few minutes from asphyxia due to laryngeal spasm and/or bronchoconstriction (particularly in asthmatics and other sensitive subjects). Lung inflammation may also occur, usually after some hours, which can also lead to varying degrees of respiratory distress.

d) 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).

e) 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 a) and b) can be fatal if the degree of exposure is sufficient.

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

a) the psychological effects of seeing fire effluents on escape behaviour in the absence of direct exposure;

b) the psychological and physiological effects of exposure to heat and toxic smoke on escape behaviour and ability;

c) the point where exposure results in incapacitation;

d) the point where exposure results in death;

In a design context the important considerations with respect to psychological and physiological considerations are to set reasonable tenability limits for occupants to remain in a place of 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.

5.4.2 Psychological effects of fire

Occupants are likely to first encounter fire effluent by seeing smoke and/or flames, and possibly sensing heat, either by coming into contact with radiant heat, or warm smoke, or hot surfaces. The effect of this initial contact on escape behaviour will depend upon the situation. The main consideration is whether the occupants are in the same room as the fire and are able to escape by moving away from the source (turning their backs on the fire) or whether it is necessary for the occupants go towards or into the effluent in order to escape (particularly if the occupant is in a place of relative safety at the time). In situations where a defend in place strategy is used, it is necessary to ensure that conditions remain sufficiently tolerable to occupants so that they will not feel forced to attempt to escape and that they will not suffer unduly from any level of exposure experienced.

If occupants are able to move away from the fire, the presence of the fire should provide an added encouragement to leave the building, and so may shorten pre-movement times compared to those from a situation where the occupants are merely responding to a warning. Alternatively, some occupants may remain to observe the fire (friendly fire syndrome) or to fight it (see references [10] and [12]). For the situation where the effluent is between the occupant and an escape route there are a number of possible outcomes which need to be evaluated with respect to the escape calculations. If the smoke and/or heat reach quite low critical values, then they may influence the occupants' choice of escape route. If the only escape route is towards the effluent, then, at a somewhat higher critical value, the occupant may decide not to enter the escape route, but to remain in situ and await rescue (for example if a room occupant feels the inner surface of the door to be hot, or looks out to find the corridor smoke logged). It is therefore necessary to consider tenability criteria for these behavioural effects. On the other hand, an occupant of a place of relative safety may feel impelled to risk moving through dense smoke and otherwise hazardous conditions if the place of refuge becomes contaminated by fire effluent or heat. Also, for any particular scenario, individual occupants vary in their willingness to move towards, through and even away from hazardous environments.

In a number of studies of fires in buildings, a proportion of people (approximately 30 %) were found to turn back rather than continue through smoke logged areas (see references [1], [14] and [15]). The average density at which people turned back was at a “visibility” distance of 3 m (optical density of 0,33 /m, 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 may also depend on whether layering permits occupants to crouch down to levels where the smoke density is lower and whether low level lighting is used to improve visibility. Based upon considerations such as these in relation to parameters such as the size and complexity of the building, it is possible to set design limits for optical density of smoke. Guidance on suitable criteria are given in references (see references [10], [12] and ISO 13571).

5.4.2.1 Inputs

Smoke optical density at the occupant location and in potential escape routes within sight of occupants.

Visual appearance of fire to occupants (flame area and height) and position in relation to occupant location and potential escape routes.

5.4.2.2 Outputs

Occupant condition:

> Likelihood that occupants will attempt escape and, in particular, whether they are likely to use a particular escape route. Escape routes should be considered unavailable if smoke logged to an extent greater than the

chosen tenability level or if a fire of critical size is between occupants and any particular escape route (see references [1], [14] and [15]).

5.4.3 Combined physiological and psychological effects of exposure to fire

The next level of threat to consider is where the exposure to fire effluent is sufficient to have direct physiological effects on occupants and which may place both physical and psychological limitations on their escape behaviour. The two major situations that need consideration are where the occupants are not enveloped in fire effluent but are exposed to heat radiation and where the occupants are enveloped in fire effluent and are directly exposed to heat, smoke and toxic gases.

5.4.3.1 Radiant heat

Radiation is important in situations where occupants must pass close to the seat of the fire in order to make an escape and in situations where occupants must pass under a hot effluent layer in order to escape. It is possible to set tenability criteria for exposure to radiation (see references [10], [16] and ISO 13571). The latter situation is important to consider since it forms the basis of many engineering design solutions. The concept is that the fire in a large room fills the roof space with a dilute smoke layer (possibly extracted), leaving clear air underneath for a sufficient time for occupants to escape. For this situation it is necessary to ensure that the layer does not descend so close to the occupants' heads that they are inhibited from passing underneath and that the downward radiation from the hot layer is not so great as to inhibit or prevent escape. A tenability limit for exposure of skin to radiant heat is approximately 2,5 kW/m^2. Below this level, exposure can be tolerated for several minutes and above which tolerance time rapidly decreases to a few seconds (approximately 4 s at 10 kW/m^2). An expression for calculating tolerance time is given in ISO 13571.

5.4.3.1.1 Input

Radiant heat flux to occupant at each time increment.

5.4.3.1.2 Output

Occupant condition:

> conditions should be considered untenable and escape routes blocked if conditions exceed the tenability limit. There is a likelihood of serious burns if occupants remain in conditions exceeding the tenability limits.

5.4.3.2 Exposure to smoke

The other situation which must be considered is when occupants are exposed directly to fire effluent. Although the main engineering design should be developed with the intention that this should not happen to a significant extent for most envisaged scenarios, it is likely that some degree of direct exposure will occur to some occupants during most fires in occupied buildings, and even a very small degree of smoke contamination can render a building uninhabitable. It is therefore important to assess what level of smoke contamination may occur through smoke mixing and circulation though the building, and what effect this may have on escape behaviour and survival.

In addition to consideration of occupants seeing smoke from afar, there is a need to consider the psychological and physiological effects of being enveloped in smoke in terms of its particulate concentration (optical obscuration) and concentrations of irritants. The main considerations are tolerability and possible impairment of escape capability and movement speeds. The requirement is to determine what levels of exposure should be considered tolerable from an engineering design standpoint and what may be the consequences of exceeding them from a risk assessment standpoint. With regard to smoke density, tenability limits are set on the basis of effects on movement speed and wayfinding ability. It is also necessary to consider what smoke density will be tolerated in a defend in place strategy.

Optically dense smoke affects wayfinding ability and the speed of movement of occupants. These effects depend upon the concentration (optical density) of the smoke and its irritancy to the eyes and upper respiratory tract. In experiments where people were asked to walk down a smoke-logged corridor, Jin (see reference [17]) found that, for non-irritant smoke, walking speed decreased with smoke density and that at an optical density of 0,5/m (extinction coefficient 1,15), walking speed decreased from approximately 1,2 m/s (no smoke) to 0,3 m/s. Under these conditions people behaved as if they were in total darkness, feeling their way along the walls. When people were exposed to irritant smoke, made by heating wood chippings, movement speed was reduced to that in darkness at a much lower optical density (optical density of 0,2/m, extinction coefficient 0,5) and the experience was found to be more distressing. Based upon these experiments and others on visibility, it is possible to set tenability limits for movement through smoke and to estimate effects on movement speed. Guidance is provided in and ISO 13571.

5.4.3.2.1 Inputs

Smoke optical density at each time increment.

5.4.3.2.2 Output

Occupant condition:

> acceptability of defend in place, acceptability of escape route use and likely degree of impairment of escape capability.

5.4.3.3 Irritant toxic gases

The effects of sensory/upper respiratory tract irritants lie on a continuum from mild eye irritation to severe pain. The effects may be assessed using the concept of a threshold concentration which if exceeded, would indicate a potentially unacceptable incidence of irritation, effects likely to make a defend in place strategy unacceptable or likely to impede or prevent the safe escape of the more sensitive occupants (see reference [10] and ISO 13571). The basic principle for assessing sensory/upper respiratory tract irritancy involves only the concentrations of each irritant at each time interval. The concentration of each irritant is expressed as a fraction of the tenability limit concentration to give a fractional effective concentration (FEC) for each irritant. The total FEC for effects due to all irritant present is then obtained by summing the individual FECs. Their sum at each time increment is then compared with a total FEC value of 1,0. If the total FEC value is less that 1,0, the severity of irritation to those exposed are considered to be acceptable and unlikely to have significant adverse effects on escape capability. Conversely, if the total FEC value is greater than 1,0, the incidence and severity of irritation for those exposed are considered to represent a significant potential for adversely affecting occupants' safe escape. Guidance on suitable FEC values and their estimation is given in ISO 13571. The effect of irritants combines with the optical density of smoke to cause impairment of visibility, with consequent effects on movement velocities and wayfinding ability (see 5.4.2.2).

5.4.3.3.1 Inputs

- Age and health status of occupants;
- Concentrations of irritant gases at each time increment.

5.4.3.3.2 Output

Occupant condition:

> satisfactory/unsatisfactory for defend in place or use of escape routes.

5.4.3.4 Asphyxiant toxic gases

The basic principle for assessing the asphyxiant component of toxic hazard involves the determination of the exposure dose of each asphyxiant gas, i.e. the integrated area under the concentration-time curve (see references [10], [11], [12] and ISO 13571). Fractional effective doses (FEDs) are determined for each asphyxiant at each discrete increment of time. Their accumulated sum is then compared with a predetermined total FED value judged to represent an acceptable incidence of incapacitation (for example 0,1 FED). If the total accumulated FED value is less than the predetermined maximum FED value (for example 0,1), the incidence of safe escape for those exposed (i.e. the probability that all occupants will be able to escape safely) is considered to be acceptable. Conversely, if the accumulated total FED value is greater than the predetermined target FED, the incidence of safe escape for those exposed is considered to be unacceptable. The initial effects of asphyxiant gases at relatively low FED values are on exercise capability. For most people this would mean that they would be capable of less exertion than normal, but be able to perform normally at low levels of exertion (such as walking). For occupants with heart conditions there could be a serious problem, such as angina pain at low levels of activity. At higher FED values, intoxication and collapse may occur in any occupants. Such effects are taken into consideration in methods for estimating asphyxiant gas FEDs and target values. Guidance is given in ISO 13571.

5.4.3.4.1 Inputs

- Age and health status of occupants.
- Concentrations of asphyxiant gases (carbon monoxide, hydrogen cyanide and carbon dioxide) at each time increment.

5.4.3.4.2 Output

Occupant condition:

> incidence of incapacitation in terms of satisfactory/unsatisfactory.

5.4.3.5 Heat

There are three basic ways in which exposure to heat may lead to life threat:

a) heat stroke or hyperthermia;

b) body surface burns; and

c) respiratory tract burns.

In the modelling of life threat due to heat exposure, it is necessary to consider only two criteria:

- the threshold for severe pain and burning of the skin
- exposures where hyperthermia is sufficient to cause mental deterioration and therefore, threaten survival.

Thermal burns to the respiratory tract from the inhalation of air containing less than 10 % by volume of water do not occur in the absence of burns to the skin of the face; thus tenability limits with regard to skin burns are normally lower than for burns to the respiratory tract (see reference [10] and ISO 13571). However, thermal burns to the respiratory tract may occur upon inhalation of air above only 60 °C when saturated with water vapour, as may occur when water content is used for fire extinguishment (see reference [12]). While occupants may be exposed to radiant heat alone without being exposed to fire effluent (see 5.4.2.1), occupants exposed to effluent may be exposed to both radiant and convected heat.

Radiant heat

> For radiant heat the main considerations are skin pain and burns. A tenability limit for exposure of skin to radiant heat is given in 5.4.2.1.

Convected heat

> For convected heat the main considerations are skin pain and burns at temperatures above approximately 121 °C and hyperthermia at lower temperatures. As with asphyxiant gases, the body of a fire victim may be regarded as acquiring a dose of heat over a period of time during an exposure and a short period of exposure to a high radiant flux or temperature is more incapacitating than a longer exposure to a lower flux or temperature. The same fractional incapacitating dose model as that used for toxic gases may be applied and, providing the temperature in the fire is stable or increasing, the fractional dose of heat acquired during the exposure can be calculated. For exposure of up to 2 h to convected heat from air containing less 10 % by volume or water vapour, it is possible to calculate an FED value for the summed effects of radiant and convected heat. Their accumulated sum is then compared with a predetermined total FED value judged to represent an acceptable probability of incapacitation. If the total accumulated FED value is less than the predetermined target FED, the probability of safe escape for those exposed is considered to be acceptable. Conversely, if the accumulated total FED value is greater than the predetermined target FED, the probability of safe escape for those exposed is considered to be unacceptable. Details are provided in ISO 13571.

5.4.3.5.1 Inputs

— Radiant heat flux to occupant at each time increment;

— temperature at location of each occupant;

— water vapour content (% by volume) at location of each occupant.

5.4.3.5.2 Output

Occupant condition:

> conditions should be considered untenable and escape routes blocked if conditions exceed the tenability limit. There is a likelihood of serious burns or hyperthermia if occupants remain in conditions exceeding tenability limits.

6 Engineering methods

6.1 General

Having established one or more trial designs and the significant fire scenarios, the depth and scope of quantification required need to be established.

The types of analysis procedure to consider include:

a) simple calculation;

b) computer based deterministic analysis;

c) probabilistic studies;

d) experimental methods.

The scope of quantification required and the type and complexity of analysis required to provide an adequate solution must be carefully considered. For instance, when considering the movement of a uniform crowd of occupants from a large, unobstructed building, simple hand calculation may be appropriate, whereas a more detailed model may be more appropriate in a case where the effect of smoke movement in the space or the presence of disable people in the population need to be considered.

In some circumstances where a quantitative analysis is not appropriate, a detailed qualitative study of results from evacuation trials may provide an effective means of arriving at a design solution.

A deterministic study using comparative criteria will generally require far fewer data and resources than a probabilistic approach and is likely to be the simplest method of achieving an acceptable solution.

The following sections discuss the major methods for evaluating occupant location and condition.

6.2 Engineering methods for evaluating occupant location

6.2.1 General

In order to evaluate occupant location during the evacuation process, it is necessary to provide estimates of the two major processes involved in evacuation, the pre-movement process and the movement process.

Research into quantifying and modelling human movement and behaviour has been underway for at least 30 years. During most of this period work on the quantification of evacuation has concentrated on the movement process. This work has progressed down two routes, the first is concerned with the movement of people under normal non-emergency conditions. The second is concerned with the development of a capability to predict the movement of people under emergency conditions such as may result from the evacuation of a building subjected to a fire threat.

Some of the earliest work concerned with quantifying the movement of people under non-emergency conditions is that of Predtechenskii and Milinksii (see reference [18]) and Fruin (see reference [19]). This research into movement capabilities of people in crowded areas and on stairs eventually lead to the development of a number of movement models.

Evacuation research is somewhat more recent. As an alternative to computer based simulation of evacuation performance, a full-scale evacuation demonstration may be used to assess a life safety design.

In more recent years attention has been increasingly directed towards the behavioural responses of occupants during emergency situations, and in particular to the behaviours included within the concept of the pre-movement process (see reference [4]), as well as other behaviours affecting the movement process, such as wayfinding behaviour. Although most research in this area has been essentially qualitative, it has been shown that the pre-movement process can require a period as long or longer than the movement process. Current research is therefore being directed at providing empirical quantitative data on pre-movement times for a variety of situations for use in engineering calculations (see references [3], [4] and [5]).

6.2.2 Modelling approaches

Attempts to simulate evacuation essentially fall into three categories of models, those which:

a) attempt to describe simple aspects of behaviour and/or movement by an equation or equations;

b) attempt to describe various aspects of human movement;

c) attempt to link movement with behaviour.

The first category of models is based simply on empirical data and empirically derived equations. These models attempt to account for individual parameters such as pre-movement times and flow rates through buildings, making use of the (effective) width of exit paths, the crowdedness of paths, the travel speed of evacuees and the effect of stairways, doors and merging flows to estimate travel flow rates and escape times. The equation(s) may be presented in simple written form or as part of a simple computer program. Typically, the equations are derived from correlations based on observations of crowd behaviour. For the most part they are based on data generated from non-emergency movement behaviour. These category one models can be used to provide reasonably good estimates of evacuation times, depending upon the assumptions made and the number of different aspects of the evacuation considered in the analysis. The limitations of these methods occur where large numbers of occupants may be involved in complex scenarios.

The second and third categories of models differ from the first in a number of ways. The most obvious being the “packaging”. While category one models are essentially an equation, category two and three models are usually represented by sophisticated computer software.

The second category of model concentrates solely on the carrying capacity of the structure and its various components. This type of model is often referred to as a “ball-bearing” or “hydraulic” model (or environmental determinism) as individuals are treated as unthinking objects which automatically respond to external stimuli. In such a model, people are assumed to evacuate the structure, immediately ceasing any other activity. Furthermore, the direction and speed of egress is determined by physical considerations only (for example population densities, exit capacity, etc.). The models assume that there are no interruptions in movement resulting from decisions made during evacuation, and that there are few if any disabled people in the population. An extreme example of this type of model is one which ignores the population’s individuality altogether and treats their egress en mass. These models typically make use of one or more of the category one models.

These second category of models tend to provide optimistic estimates of time to evacuate a building and no real-life evacuation should be expected to be completed as quickly. One serious limitation is that they seldom include any but the most perfunctory consideration of pre-movement process behaviours, which may take up a large proportion of the total time required to evacuate in practice. The complexity of individual behaviours during the movement process tend also to be rather simplistically represented. Studies have indicated that highly organized evacuation systems in large office buildings may result in evacuation times as much as twice those predicted by some models and where there has been a poor standard of training and organization, the evacuation times can be as much as three times the predicted time.

As with the first category methods, the success of the second category of models depends upon how their use, the assumptions made and the variables considered. They can provide useful components of an overall assessment. However, because they are often provided as computer packages, there is a danger that important aspects of the evacuation may be omitted if they are used as “black box” solutions to evacuation time calculations.

The third category of models takes into account not only the physical characteristics of the enclosure but treats the individual as an active agent. It takes into consideration response to stimuli such as the various fire hazards, and individual behaviour such as personal reaction times, exit preference, etc.

This third category of models vary in their complexity and sophistication, but potentially can provide the most complete estimates of evacuation time, taking into account a wide variety of variables. As with the other two categories they are only as good as the parameters included and the assumptions made. As fundamental data on many aspects of human evacuation behaviour exist only in a rudimentary form, the predictive power of the models is limited. There are also limitations on the extent to which they have been validated against real evacuation data. Nonetheless, they do represent powerful and useful tools and are continually improving.

A variety of different modelling methodologies are available for category two and three evacuation models. Within the modelling methodologies adopted, there are also a number of ways in which to represent the enclosure, population and the behaviour of the population.

Examples of the first category of models available for estimating the time necessary to complete the evacuation of a building can be found in the *SFPE Handbook* (see references [6] and [7]). In the following sections an attempt is made to describe the modelling methodologies adopted for the second and third category of models. A more complete description of these models may be found in reference [20].

6.2.3 Evacuation modelling methodology.

The nature of an evacuation model is dependent on several factors, namely, the intended purpose of the model (see 6.2.3.1), the method used to represent the enclosure (see 6.2 3.2), the population perspective adopted (see 6.2.3.3) and the behavioural perspective used (see 6.2.3.4).

6.2.3.1 Nature of model application

While all the models under consideration address the common problems of evacuation, they handle this problem in three fundamentally different manners: optimization, simulation, and risk assessment. The underlying principles of each of these approaches influences the associated model capabilities.

One approach to modelling evacuation assumes that occupants evacuate in as efficient a manner as possible, ignoring peripheral and non-evacuation activities. The evacuation paths taken are considered optimal, as are the flow characteristics of people and exits. These models tend to cater to a large number of people or treat the occupants as a homogenous ensemble, thus not recognizing individual behaviour. These models are generally termed optimization models.

Alternatively, designers may attempt to represent the behaviour and movement observed in evacuations, not only to achieve accurate results, but to realistically represent the paths and decisions taken during an evacuation. These models are termed simulation models. The behavioural sophistication employed by these models varies greatly, as does the accuracy of their results.

Risk assessment models attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures can be assessed.

6.2.3.2 Enclosure representation

In all evacuation models, the enclosure in which the evacuation takes place must be represented. Two methods are usually used to represent the enclosure: fine and coarse networks. In each case, space is discretized into subregions, and each subregion is connected to its neighbours. The resolution of this subdivision distinguishes the two approaches.

In the fine network approach, the entire floor space of the enclosure is usually covered in a collection of tiles or nodes. The size, shape and connectivity of a node may vary from model to model. A large geometrical network may be composed of thousands of nodes and each compartment may be made up of many nodes. In this way, the geometrical network together with its internal obstacles may be represented to the extent that each individual may be accurately located at any time during the evacuation.

In the coarse network approach, the geometry is defined in terms of partitions derived from the actual structure, possibly including a corridor, a room, etc. Each node may represent a room or corridor irrespective of its physical size. Nodes are connected by arcs representing actual connectivity within the structure. In such a model, occupants move from segment to segment and their precise location is less defined than in fine network models. For instance, an occupant may be represented to move from room to room and not from one area to another inside the same room.

In this approach, local movement and navigation including overtaking, the resolution of local conflicts and obstacle avoidance are all difficult to incorporate into the model. Consequently, the exact location of an individual is not represented and any detailed calculations of individual movement and interactions between individuals cannot be made.

The difference between these two types of network models becomes increasingly indistinguishable when the evacuating population is treated as a homogenous ensemble.

6.2.4 Population perspectives

The enclosed population can be represented by one of two approaches: an individual or a global perspective. Most models allow for personal attributes to be assigned, either by the user, or through a random device. These personal attributes are then used in the movement and decision-making process of that individual. This process is typically independent of other occupants involved in the simulation, and allows for the individual trajectories/histories to be followed. The models that are based on this individual perspective can then represent a diverse population, with different internal traits whose evacuation, in some manner relies on these traits. It is important here not to confuse independent decision-making with an inability to implement group behaviour. The concept of the individual does not preclude group behaviour, but examines each occupant individually, then allocates an action which may be considered as group behaviour.

Other models do not recognize the individual, but delineate a population as a homogenous ensemble (or grouping), without different identities, thus adopting a global perspective. These models represent evacuation details not on the basis of which individuals escaped, but on the numbers of occupants who escaped. This approach may be beneficial in both the management and the speed of the models, but lacks much of the detail available to the individual perspective.

When employing a global perspective, it is difficult to model the effects of events on individual occupants (the effect of toxic fire gases, for instance). Only a distributed, or average effect can be established throughout the population. This gives no indication, for example, of the survival rates of specific groups of individuals, such as the elderly or the disabled, but instead, only that of the proportion of the population affected.

This problem arises for a number of other evacuation factors including any individual attribute, communication, response of the individual to cues, and interaction of an individual or subgroup with the rest of the population. This deficiency may not be considered serious in simple, homogenous populations, but in more realistic situations, would seriously hinder an accurate understanding of the behaviour of the population.

6.2.4.1 Behavioural perspective

To represent the decision-making process employed by occupants in an evacuation, the model must involve an appropriate method for determining behaviour which will be influenced by the population and geometry approaches taken. As such, it is possibly the most complex of all the defining aspects.

Broadly speaking, the models investigated can be separated into the following five behavioural systems:

a) no behavioural rules;

b) functional analogy behaviour;

c) implicit behaviour;

d) rule-based behavioural system;

e) artificial intelligence-based behavioural system.

Models which apply no behavioural rules rely completely on the physical movement of the population and the physical geometrical representation to influence and determine the occupant evacuation. In these models, decisions are made only on the basis of physical influences.

Functional analogy behavioural models apply an equation, or set of equations, to the entire population which then completely governs the population’s response. Although it is possible for the population to be defined individually in these models, all the individuals will be effected in the same way by this function, and therefore will react in a deterministic manner to its influences, undermining individual behaviour. This function is not necessarily derived from real-life occupant behaviour, but is instead taken from another field of study assumed to be analogous to human behaviour, (for example fluid flow, magnetic fields, etc. taken from physics). Occupant movement and behaviour is then completely determined by this function, which may or may not have been previously calibrated with human movement.

Some models do not specify behavioural rules, but instead assume them to be implicitly represented through the use of complicated physical methods. These models may be based on the application of secondary data, which incorporates psychological or sociological influences. These models therefore rely upon the validity and accuracy of this secondary data.

Models which explicitly recognize the behavioural traits of individual occupants, usually apply a rule-based system. This allows for decisions to be taken by occupants according to pre-defined sets of rules. These rules can be applied in specific circumstances, and in such circumstances, have an effect. For instance, a rule may be:

> “If I am in a smoke-filled room, I will leave through the nearest available exit.“

A problem with this style of a decision-making process is that in simplistic models the same decisions are taken, under the same circumstances, in a deterministic fashion. This has the disadvantage of denying the possibility of natural variations in outcomes through repetition. Most of the rule-based models are stochastic. However, several models incorporate a contribution of both deterministic and stochastic approaches, depending on the circumstances.

Recently, artificial intelligence has been applied to behavioural models, where individual occupants are designed to mimic human intelligence, or an approximation of it, in respect to the surrounding environment.

The behaviour which can be expected in evacuations has a complex relationship with the surroundings. An individual may be involved in three types of interaction during an evacuation, all of which are associated with complex decisions. These encounters may be categorized as:

a) people-people interactions, i.e. interactions with other occupants;

b) people-structure interactions, i.e. interactions with the enclosing structure;

c) people-environment interactions, i.e. interactions with the fire-affected atmosphere and possible debris.

These interactions will affect an occupant’s movement, and will therefore utilise a decision-making process. This process is further complicated by the way in which this interaction takes place. This may occur on three levels:

a) psychological: an interaction of this type under a fire threat may entail an occupant rearing away from the fire;

b) sociological: an interaction of this type under a fire threat may cause an occupant to instigate a rescue of another occupant;

c) physiological: an interaction of this type under a fire threat may result in intoxication due to narcotic fire gases.

As identified earlier, human behaviour is the most complex and difficult aspect of the evacuation process to simulate. No model to date fully addresses all the identified behavioural aspects of evacuation. However, several models have attempted to incorporate a number of these behavioural interactions. Furthermore, not all these behavioural aspects are fully understood or quantified.

6.2.5 Experimental methods

As an alternative to computer methods, a full-scale evacuation demonstration can be held to assess a life safety design. The full-scale evacuation demonstration involves staging an evacuation exercise using a representative target population within the structure (see reference [20]). In most real emergency evacuations it is to be expected that the majority of occupants would never be directly aware of or come into contact with fire effluent. To this extent experimental evacuations can be considered realistic models of emergency evacuations provided the occupants are not pre-warned. However, since occupants cannot be subjected to trauma or panic nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, such an exercise provides little useful information regarding the suitability of the design in the event of incidents in which the design fails to such an extent that life threatening conditions occur. Information on this topic is available from studies of actual incidents, although it is often not possible to obtain full quantitative data on such incidents.

On a practical level, when evacuation drills are performed, usually only a single evacuation trial is undertaken, which from a design point of view, does not provide sufficient information to arrange the layout of the structure for optimal evacuation efficiency. Also, it is only possible to conduct such trials after the structure has been constructed. In practice, for any different combination of structure, population and fire scenario, repeated evacuations would be expected to follow a distribution of outcomes. However, even a single experiment can provide an indication of how the evacuation of the structure is likely to occur for a given population and fire scenario.

6.2.6 Verification of evacuation models

The verification of evacuation models is an essential step in the continual development and acceptance of these tools. While no degree of successful verification will PROVE an evacuation model correct, confidence in the model is established the more frequently it is shown to be successful in as wide a range of applications as possible. At their present stage of development, there is a shortage of convincing quantitative verification history for evacuation models. This is mostly due to the scarcity of suitable experimental benchmark evacuation data. The majority of evacuation trials are conducted to demonstrate the suitability of a building design and/or staff procedures or to gauge compliance to a regulation or standard, but not for model verification purposes. In most of these cases, insufficient data is recorded to allow a detailed verification of evacuation models. The variability of human behaviour compounds these problems making repeatability of experiments an issue. Even under the most controlled experimental conditions, no evacuation exercise involving crowds of real people will produce identical results when the exercise is repeated, although the same people have been used. Verification of evacuation models should follow a systematic and measured approach. This can involve:

a) component testing: routine checking of major software subcomponents;

b) functional validation: checking of model capabilities and inherent assumptions to be compatible with intended use;

c) qualitative verification: comparison of predicted human behaviour with informed expectations;

d) quantitative verification: detailed comparison of model predictions with reliable experimental data.

Viewed in this manner, verification is an on-going activity and an integral part of the life cycle of the software.

6.3 Engineering methods for evaluation of occupant condition

6.3.1 General

Two major considerations with regard to engineering methods for the evaluation of occupant condition are the choice of methods applicable to different design situations and the technical basis for choices of tenability limits in relation to the condition assessment methods currently available.

6.3.1.1 Choice of methods

For most building design strategies, the objective is to ensure that occupants are able to leave the building or remain in a place of relative safety during a fire without ever coming into contact with fire effluent or heat. For a simple deterministic design, it may be sufficient to demonstrate that no exposure to fire effluent of heat occurs at any occupied place at any time during the engineering simulation. It may be possible to ensure that this is the case for a range of design fire scenarios, for example in situations where the fire, fire effluent and heat are contained within an unoccupied enclosure. Where the fire occurs within an occupied enclosure, it may be possible to prevent occupant exposure. For example, engineering methods in relation to smoke control are usually applied to smoke filling time and smoke extraction. The design is usually intended to maintain a hot buoyant smoke layer well above head height so that occupants are not exposed to smoke. The design fails if the smoke layer descends to a level exposing the occupants. In this context the tenability limit is that no smoke or heat exposure is acceptable. Such methods are often applied to large enclosures such as shopping malls or atria.

Separation between occupants and fire effluent and heat can theoretically be achieved, although in practice some exposure may occur. For instance, occupants may be subjected to heat radiation from the buoyant, hot upper layer. Thus, it is necessary to ensure that this will not impede escape or cause injury. Furthermore, when a fire occurs within an occupied enclosure it is inevitable that there will be some effect on the occupants, i.e. they may be able to see smoke or flames or those close to the fire may be exposed to heat. In many situations where the fire is in a separate enclosure from the occupied enclosures, smoke mixing or smoke penetration through gaps or air circulation systems may result in contamination or spaces beyond the fire enclosure. In all these situations any design that relies on no exposure of occupants will fail, so that in practice it is necessary to use design criteria that allow some sight of, or some degree of exposure to, effluent or heat. For such situations it is necessary to use tenability criteria for exposure. For simple situations it may be sufficient to use criteria for a few key parameters, such as smoke density, carbon monoxide, temperature and heat flux at the location of each occupant.

The main challenge from an engineering point of view is to be able to make reasonable estimates of the conditions at each occupant location (most importantly at head height).

For other design situations it may be necessary to carry out a more detailed assessment of occupant condition. This is particularly important in risk assessments, when the effects of a range of fire scenarios are under consideration, including less likely scenarios which may involve significant exposure of occupants to fire effluent or heat. Such assessments may require estimation of hazards of injury, incapacitation or death for particular scenarios, involving the full range of effects on occupant condition.

6.3.1.2 Technical basis for choices of tenability limits and hazard assessments

Methods for estimating the condition of occupants are directed at evaluating psychological and physiological factors affecting their evacuation ability or behaviour, their state of health and their survival. Initial considerations relate to the general ability of the occupants to evacuate. Such decisions are usually qualitative, based upon the occupancy type and the knowledge of the abilities of the occupants.

Assuming occupants are considered able to perform an evacuation, the next consideration is their likely psychological reaction to seeing a fire or smoke. With regard to sight of a fire, in practice it is normally assumed that occupants will not move towards a fire, so that an escape route is considered unavailable if the fire is between the occupant and the escape route. It is also assumed that occupants will move away from a fire and evacuate any enclosure containing a fire. This is often not the case, at least during the early stages of a fire, so that fire safety management strategies should be developed to ensure that occupants evacuate when required.

Another consideration is how occupants will respond to seeing smoke and, for example, how this will affect the decision to use a particular escape route.

Beyond these purely psychological aspects of occupant condition are considerations of effects on occupants of direct exposure to fire effluent and heat. These range from further psychological effects on aspects such as exit route choice, through physiological effects on escape speed and efficiency to estimates of incapacitation and lethality. Considerations related to the quantification of these effects and the determination of tenability limits are discussed in the next sections. Details of calculation methodology for physiological endpoints from the effects of smoke obscuration, irritancy and incapacitation from asphyxiant gases are given in the companion standard ISO 13571.

With regard to all these psychological and physiological variables there are a number of difficulties in arriving at objectively derived and accurate tenability limits or hazard end points. One set of difficulties arises from the extreme range of variations within the human population with regard to both psychological and physiological characteristics. This applies both within what may be regarded as the "normal" population, as well as with regard to special groups in relation to parameters such as age, abilities and health status. Although it is possible to make reasonable predictions of how most occupants will react to particular situations and the time required for them to respond, individuals are capable of making complex and varied responses to situations. Considering the physiological effects, the young, elderly and people with particular health problems may be seriously affected by effluent or heat at much lower levels than other members of the population.

Another problem is that many of these parameters have not, or cannot be, directly quantified. In considering the psychological or behavioural effects, it is difficult to create realistic experimental scenarios to measure such effects as "willingness to enter smoke-logged escape routes". Studies of behaviour in actual incidents lack accurate data on parameters such as optical density and rely on the memory and subjective assessments of witnesses who are likely to be influenced by particular features from which it is difficult to derive realistic generalized, quantitative criteria. It is in most cases not ethically possible to expose subjects to realistic conditions either for mixed fire effluent or individual toxic species for the purpose of determining physiological effects. Consequently, it is necessary to rely on data obtained from a limited range of human experimental exposures (usually at low levels), anecdotal data from accidental human exposures in fires or industrial incidents, and experimental animal studies.

The best that can be done in such a situation is for experts on the subject to review as much or the available data as possible and agree on recommendations for tenability limits and hazard estimation methods. An attempt has been made to do this particularly for physiological criteria in ISO 13571. Where tenability assessment relies on minimal, subjective, or poorly quantified data, it is necessary to use conservative estimates for maximal safe exposure levels. The following sections contain comments on the main parameters needed for use in hazard assessments.

6.3.2 Assessment of psychological effects of seeing fires and smoke and heat

Although sight of smoke or fire may have a number of influences on occupants the most important consideration in engineering design is the extent to which smoke or fire on an escape route is likely to result in occupants being unwilling to use the route. This will depend to some extent on the particular situation and the particular occupants, but some indications of approximate optical density and willingness to enter have been made from studies of fire incidents (see 5.4.1). These may be used as part of the criteria for exit choice in egress time calculations. For the effects of fire, the best that can be done currently is to apply radiation tenability criteria. Thus occupants may be expected to pass close to a fire provided they are not exposed to painful levels of radiation.

While such effects may be important in practice in determining the egress patterns and escape times from occupied enclosures during fires there are limited data available for setting tenability limits. Although the recommended limits are considered suitable, these may be improved by further research. Special criteria may need to be applied to particular occupancy types.

6.3.3 Assessment of behavioural and physiological effects of exposure to smoke

In addition to the psychological effects of seeing smoke on exit choice, there may be similar effects once occupants become exposed to smoke. They may decide to continue of turn back. If they decide to continue, smoke also affects the speed of movement of occupants. These effects depend upon the concentration (optical density) of the smoke and its irritancy to the eyes and upper respiratory tract. These effects on movement speed have been quantified in a series of experiments by Jin (see reference [17]) which provide a reasonable basis for egress calculations.

Based upon considerations such as those described for the optical density and irritancy of the smoke, it is possible to set tenability limits for smoke density appropriate to particular fire scenarios in relation to the physiological effects on the ability of occupants to see sufficiently well to escape efficiently as well as possible psychological effects on their escape behaviour. Appropriate limits will depend upon the building and occupant characteristics. For example, for small spaces with short travel distances to exits, it may be possible to set less stringent tenability criteria if occupants are familiar with the building. For large spaces it may be necessary to set more stringent tenability limits, particularly if occupants are likely to be unfamiliar with the building and need to be able to see much further in order to orient themselves to find exits. To evaluate the effects of irritancy on the ability to see, it may be necessary to use more stringent smoke density tenability criteria for scenarios where the smoke evolved is likely to be highly irritant to the eyes. Other factors to be taken into consideration would be the complexity of the space, the lighting and the visibility of the signs.

This is another area where further experimentation would be valuable (see 5.4.2.2) There are ethical limitations on the extent to which human subjects can be exposed to irritant smoke, but this can be important in accidental fires. Some guidance on the subject is provided in ISO 13571.

6.3.4 Engineering methods for evaluating incapacitating effects of fire effluent and heat

Throughout the time course of the fire the condition of the occupants is evaluated with respect to any exposure to fire effluent and heat. For some of the hazards (irritants, smoke density and radiant heat) the most important parameter is the concentration or intensity of the hazard, for others (asphyxiant gases and convected heat) the most important parameter is the “exposure dose”, i.e. the integrated area under each concentration-time curve (see references [10], [11] and [12]).

The basic principle for assessing the sensory/upper respiratory tract irritant component of toxic hazard analysis involves only the concentrations of each irritant (see ISO 13571)] . Fractional effective concentrations (FECS) are determined for each irritant and the point in time is calculated at which their sum reaches a predetermined value judged to represent an acceptable incidence of human incapacitation.

The basic principle for assessing the asphyxiant component of toxic hazard analysis involves the exposure dose of each toxicant. Fractional effective doses (FEDs) are determined for each asphyxiant and the point in time is calculated at which their sum reaches a predetermined value judged to represent an acceptable incidence of human incapacitation.

Incapacitation due to asphyxiants and incapacitation due to sensory/upper respiratory irritation are considered separately. Although FED values are considered to be additive with each other and FEC values are considered to be additive with each other, FED and FEC values must not be added together. The effects of smoke on visibility and the effects of radiant and convected heat are also considered separately. It is possible to sum the effects of radiant and convected heat, but in practice there is little error in treating them separately. Methods for assessing both the heat and the visual obscuration components of fire hazard analysis use empirical relationships derived from experience with human subjects.

When evaluating physiological effects on occupants there are two aspects to consider, the types of effect (in terms of their nature and severity) and the exposure thresholds for the effects. For any given toxic or physical hazard, the exposure thresholds for particular effects and the severity of the effects vary for different individuals in the population. The frequency distributions of these thresholds for different effects have not been determined for the human population, but no precise information is available on the shape of these distributions.

The methodologies described herein are intended to predict times to the occurrence of biological responses of humans exposed to fire effluents. However, the calculated time to a response, such as incapacitation, represents the maximum in a statistical distribution of subjects’ responses surrounding that time, i.e., the mode, or most frequently expected time for the response to occur for exposure of a number of subjects. Individual times to the response would be statistically distributed around the mode in a probability curve. Thus, with incapacitation as an example, there is some probability of incapacitation occurring well before the predicted time, just as there is some probability of incapacitation occurring much later than would be predicted. The predicted time to incapacitation is only the time at which there is the maximum probability of incapacitation occurring.

The setting of criteria for life safety and the predicted ability of occupants to escape and/or be rescued from a fire situation must take into consideration the expected frequency distribution of human responses relative to total exposure levels. An exposure level of 1 represents the mode, so that at this time approximately 50 % of exposed occupants would be expected to be incapacitated, while an exposure level of 0,2 corresponds to a much smaller percentage of the exposed population being incapacitated. The effects upon the remainder of the population depends upon the nature of the hazard. For asphyxiant gases effects of exposure tend to be relatively minor until a reasonably well-defined threshold is reached, when collapse and loss of consciousness occur following a brief period of intoxication. For eye and upper-respiratory-tract irritants the effects lie on a continuum of increasing severity from mild eye and throat irritation to severe pain and breathing difficulties leading to the cessation of effective escape attempts. In order to predict the effects on the escape capability and condition of the occupants it is necessary to identify two points on this increasing severity scale. One is the point where eye and upper respiratory tract pain and breathing difficulties are sufficient to interfere with escape attempts (rendering movement though a building slower and more difficult or inhibiting occupants from passing through smoke-logged areas on potential escape routes). The other is the point where effects become so severe that escape attempts are likely to cease, a degree of incapacitation approximately equivalent to collapse from asphyxiant gases. Each of these endpoints will have a frequency distribution for the population and there is likely to be some overlap between the distributions of the two effects. Thus, for an exposure level at which half the population are experiencing effects on escape efficiency, a small proportion are likely to be severely incapacitated.

It is important to make some estimate of the effects that are likely to delay escape possibly resulting in fewer occupants being able to escape during the short time before conditions become so bad that escape is no longer possible. Most important in this context is exposure to optically dense and irritant smoke which tends to be the first hazard confronting fire victims. For more severe exposures, a point may be reached where incapacitation is predicted to be so severe as to prevent escape. It is considered important to attempt some estimate of the point where conditions become so severe in terms of these hazards that effective escape attempts are likely to cease, and where occupants are likely to suffer severe incapacitation or injuries. In the following sections some data are presented from which tenability criteria may be set.

a) Pre-existing disabilities of subpopulations

   Essentially all toxicological data relative to gaseous fire effluents have been derived from laboratory experiments using young healthy animal surrogates or young healthy humans. A limited number of experiments have been carried out at very low concentrations of asphyxiant gases and irritants found in fires on humans with pre-existing disease conditions. The overall human population contains a number of subpopulations which exhibit greater sensitivity to various fire effluent toxicants, principally due to compromised cardiovascular and pulmonary systems. Two of the largest such subpopulations are the elderly and the approximately 15 % of children and 5 % of adults who are asthmatic (see reference [21]). The elderly and particularly those with impaired cardiac perfusion are particularly susceptible to asphyxiant gases. Thus, the average lethal carboxyhaemoglobin concentration in adults dying in fires or from accidental CO exposure is lower in the elderly. Also it has been shown in experimental studies that time to the onset of pain in an exercise test is significantly reduced by as little as 2 % carboxyhaemoglobin in angina sufferers. This could be very important when attempting to escape from a fire. Asthmatics, (and sufferers of other lung conditions such as chronic bronchitis and reactive airways dysfunction syndrome) are particularly susceptible to bronchoconstriction upon even brief exposure to very low concentrations of irritants, and with distress, severely reduced aerobic work capacity, possibly results in collapse and death depending upon the sensitivity of the individual and the severity of the exposure. It is the objective of fire safety engineering to ensure that essentially all occupants, including the sensitive sub-populations, should be able to escape safely without their experiencing or developing serious health effects. Thus, safe levels for exposure of the human population to fire effluent toxicants must be significantly lower than those determined from experiments with uniformly healthy animal or even human surrogates.

b) Ventilation effects in relation to activity levels, inhaled carbon dioxide concentrations and body size

   In addition to the concentration of inhaled toxic products and the duration of exposure, another variable that can profoundly influence escape capability and time to incapacitation is the level of ventilation, i.e. the volume of breathed air per minute. This is because the rate of uptake of toxic products, particularly asphyxiant gases is directly proportional to the level of ventilation. Ventilation can vary by approximately an order of magnitude between a state of rest and that of performing heavy work. Similarly the level of ventilation also depends upon the inhaled carbon dioxide concentration. The two effects may be considered as basically additive. Furthermore, the level of ventilation per unit body mass is increased as body mass decreases, i.e. babies and children have an increased rate of uptake of asphyxiant fire gases compared with adults. For these reasons, the exposure doses shown in this part of ISO 13387 are those likely to produce incapacitation at a level of light adult work. Lower exposure doses may be applicable in situations of heavy work, or when considering work in children. An example may involve escape up stairs. The effects of inhaled carbon dioxide are taken into consideration in ISO 13571.

c) Quality of tenability criteria and hazard assessment methods for irritants, asphyxiants and heat

There are a number of difficulties involved in setting criteria for physiological effects on human subjects in fires including the following:

- for ethical reasons, it is not possible to carry out experimental studies at the levels found in real fires;
- there is a great variation in response within the human population;
- toxic effluents consist of complex mixtures with unknown interactions and some toxic endpoints are hard to define.

A difficult area is the prediction of the effects of irritants on escape efficiency. This is partly because the effects lie on a continuum from mild eye irritation to intense pain, depending upon the exposure concentration, so as to define precise endpoints is difficult. It is not possible to conduct experiments on humans and it is difficult to extrapolate simplistic behavioural or physiological paradigms from data obtained in animal experiments to predict likely effects on human escape capability. It is also difficult to quantify variations in sensitivity within the human population. Furthermore, only a small proportion of the irritant species occurring in fire effluent have been studied. For these reasons, it has been difficult for experts to agree on tenability limits, although suggested limits are presented in ISO 13571. Due to the ethical limitations associated with research in this area and increasing restrictions on animal experimentation, it is likely that some uncertainties will remain. The methodology can possibly be improved by more detailed investigations of human exposures during fires and industrial incidents involving irritant fumes.

The incapacitating effects of individual asphyxiant gases have been the subject of a considerable amount of work in humans, non-human primates and rodents. There is a reasonably well-defined endpoint which is the point of loss of consciousness. There is a number of uncertain areas which may be addressed with further experimental work in humans or non-human primates, but work in this area is subject to increasing restrictions so that much further improvement in the models is unlikely. The main areas of uncertainty involve interactions within gas mixtures, variations in susceptibility within the human population and long term health effects of exposures. The most studied gas is probably carbon monoxide. For this gas there are good physiological data for human incapacitation and some indications of the range of susceptibility across the populations, particularly for lethality. There are currently concerns about the long term neurological effects of exposures at moderate levels. The acute effects of low oxygen hypoxia are also reasonably well understood from human studies. The acute effects of hydrogen cyanide are less well quantified, but good data are available from non-human primate and dog studies. These have been used to predict effects in humans and correlated with accounts of accidental and experimental human exposures. The hypoxic effects of the inhalation of irritants have not been well quantified and in particular their interaction with the effects of other asphyxiants. A limited amount of work has been carried out on mixtures of asphyxiant gases.

Despite these areas of uncertainty the effects of asphyxiant gases on humans are relatively well understood. It is therefore considered that the predictive power of the asphyxiation models is relatively good and adequate for use in engineering calculations. Detailed guidance is provided in ISO 13571.

A number of detailed studies have been made of the effects of humans exposure to radiant heat. There is generally good agreement between these studies and relatively good predictions of time to pain and burns can be made for areas of naked skin. The effects of exposure to convected heat have been studied to a lesser extent. In particular the effects of water content on time to pain from naked skin exposure or inhaled hot air may be improved by further evaluation. Further details are provided in 5.4.3.5 and ISO 13571.

Annex A
(informative)

Building and occupant information

The characteristics of a building and its occupants which can affect the location and condition of the occupants include the following.

A.1 Building characteristics

A.1.1 Building layout and geometry

The extent to which a developing fire, other people and alternative exit routes are likely to be visible to the occupants of a building can be significantly affected by the variety of occupancies and settings and the occupants comprehension of alternative layouts and ease of wayfinding. This layout can have a major influence on the time it takes occupants to start to move in an emergency and to the extent that evacuees outside the building are moved to predetermined assembly points. These must all be considered so as to avoid congestion and to ensure access for the fire brigade.

A.1.2 Escape routes

Escape routes accessible to all the occupants is an essential design prerequisite. Confusing spatial layouts are best avoided. The efficient, effective and safe use of escape routes can be improved by provision of adequate lighting.

A.1.3 Doors

The position, opening direction and closing forces of doors can materially affect the movement process, as can the results on door opening of an pressurization systems.

A.1.4 Fire alarm or cue

The type of warning (whether a simple alarm bell or siren, informative visual displays, non-directive pre-recorded public announcements or live directive announcements from a control room with closed circuit television facilities), or cue (such as visual recognition of fire or the behaviour of other occupants), received by the occupants will significantly affect their response.

The content of warning system messages is critical to their effectiveness. The effectiveness of verbal guidance can be seriously diminished if it is stated in terms of directional bearings, relative positions or the names given to the various entrances which are not apparent from within the building.

A.1.5 Signs and lighting

The choice, positioning and informational content can materially assist with the movement process.

A.1.6 Refuge areas

In some buildings it may be necessary to provide spaces designated as refuge areas to facilitate the ordered evacuation of occupants. Consideration needs to be given to the length of time which evacuees may be required to remain in these areas in terms of appropriate levels of fire endurance and protection against the ingress of smoke. Furthermore, facilities for communication with building management and fire brigade, comfort (resting) and first aid may be provided.

A.1.7 Wind speeds

The smoke control systems used in many buildings remove smoke and heat through an exhaust, replacing it with fresh air from outside. The incoming air can attain relatively high velocities in the aperture where it enters the building.

In circumstances where escape routes are used as the path for replacement air, it is necessary to consider the effect on occupants utilizing escape routes of incoming wind currents.

A.2 Occupant characteristics

A.2.1 Population numbers and density

The occupant capacity of a room is the number of persons expected to be present. Where there is no other information available, the number should be estimated according to use, i.e. by dividing the area of the room or storey by an appropriate value of floor space factor. However, where actual occupancy load data are available for similar occupancies, these may be used. Useful information regarding occupant densities is often provided in national codes.

Situations may prevail where codified information is not sufficiently accurate for the particular design under consideration. In such circumstances, the designers may have to access other data sources or generate the data by, for example, carrying out surveys of a particular premises. Designers should be mindful that the numbers and distribution of occupants in a building may change with time, activity and season of the year.

A.2.2 Familiarity with the building

Occupant response is greatly influenced by their familiarity with the building and its systems. Occupants who are frequent users of the building may be expected to have a good knowledge of the nearest and alternative escape routes and warning systems. They may be expected to make an efficient evacuation, particularly if subjected to emergency training and evacuation drills. Occupants who are infrequent users of the building, such as members of the public, will be more likely to attempt to leave by the route they entered the building. They will depend more upon signs and may be less familiar with, and responsive to, warning systems.

A.2.3 Distribution and activities

The pattern and timing of an evacuation will depend upon the extent to which occupants are evenly distributed throughout the occupied spaces or concentrated in particular locations. The initial response may be affected to some extent by the activities engaged in immediately before the fire. It may be important to obtain pre-movement time data for occupants engaged in different activities (such as eating in a restaurant, shopping, watching a film or entertainment, sleeping, working).

A.2.4 Alertness

The involvement of people in, and commitment to, the activities being carried out within the building or their interaction with the other occupants of the building can effect their awareness of other circumstances. For instance, if people are in bed and asleep then their response times to a fire alarm can be expected to be considerably delayed.

A.2.5 Physical and mental ability and mobility

In many buildings a proportion of the population will be disabled (mentally and/or physically). Some of the occupants will be immobile and will rely entirely on the actions of others to effect their evacuation (if necessary) from the building.

The initial response of many disabled people may involve considerably additional preparation work prior to movement. The movement of disabled occupants can be significantly influenced by the nature of their disability and building elements such as doors, ramps and stairs.

A.2.6 Social affiliation

The behaviour of occupants will be significantly influenced by whether they are alone or with a group. Sometimes this contributes to people starting to move more quickly in response to fire cues but does not necessarily result in direct movement by separated group members towards the nearest exit route as they are likely to re-establish the group. In addition the speed of movement will often be dictated by that of the slowest member of the group.

A.2.7 Role and responsibility

The role and responsibility of an occupant during the normal use of the building will, in an emergency influence their behaviour and the behaviour of others. It follows that a high ratio of well trained and authoritative staff compared to other occupants of members of the public will provide an opportunity to shorten the ambiguous, information gathering phase which is a feature of pre-movement time.

A.2.8 Location

For each individual occupant their location in relation to the fire, the warning system and the escape routes will affect their responses.

A.2.9 Commitment

People are action and goal orientated and have reasons for being in a particular place. Those reasons will continue to guide their behaviour even when an emergency occurs.

A.2.10 Focal point

If the setting has a particular focal point, such as a stage in the theatre, the population of the building will normally look to that point for guidance in the first stages of an alarm and evacuation.

A.2.11 Responsiveness

The responsiveness of occupants to an emergency situation depends on a variety of factors, including the extent to which they are committed to other activities, their mental and physical state, the extent to which they are familiar with and trained to respond to warnings, the extent to which they feel threatened by the fire, their role and responsibilities.

A.2.12 Occupant condition

The condition of occupants before the emergency is determined by their physical and mental condition. Throughout the time course of the fire their condition depends upon the results of the analysis of occupant condition which is carried out at the same time as the analysis of occupant location. At each time step in the analysis the evaluation of the location, to some extent, will be dependent upon the results of the analysis of the occupant condition.

Annex B
(informative)

Firefighting and rescue facilities

It is important to consider the potential of the local fire brigade for firefighting and rescue, the occupant and building parameters and the fire spread and development scenarios. An analysis, where necessary in liaison with the fire brigade, should be carried out to evaluate fire brigade response times and/or procedures, equipment, facilities and water supplies available, before considering what additional facilities are necessary in the building design to assist the fire brigade.

Firefighting and rescue operations are extremely difficult to quantify because of the wide range of variables involved. The factors that have to be taken into account include:

a) the time to arrival of fire services and firefighting resources;

b) the availability of specialist appliances and equipment;

c) the precise nature and location of the fire incident;

d) the location and condition of persons requiring assistance during the evacuation (or rescue if the life safety design system has failed).

The design of the building and the facilities provided can now be reviewed to ensure that:

a) there is sufficient means of external access to enable fire appliances to be brought near to the building for effective use;

b) there is sufficient means of access into, and within, the building for firefighters to assist in the evacuation, to effect rescue (where necessary) and to fight fire;

c) the building is provided with sufficient fire mains and other facilities to assist firefighters in their tasks;

d) the building is provided with adequate means of venting heat and smoke from basement areas;

e) the structural response of the building is sufficiently robust to ensure that fire fighters are not injured by structural failure.

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