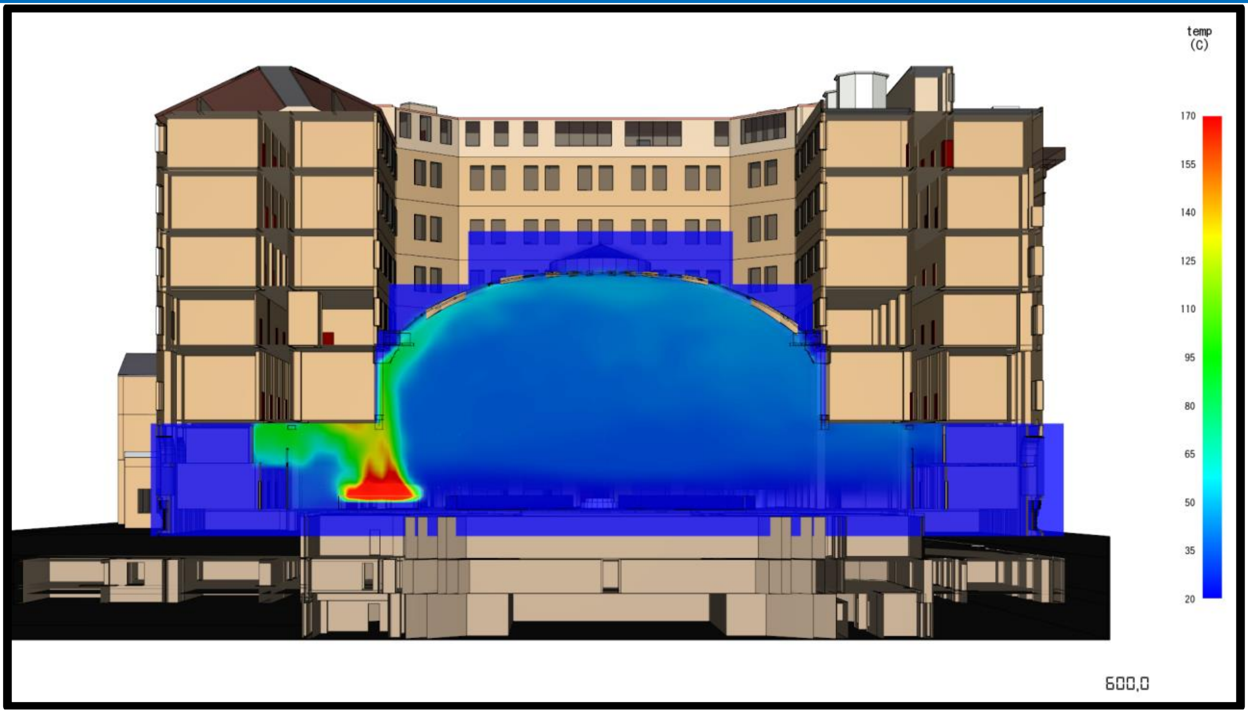
Fire safety engineering concerning evacuation from buildings

CFPA-E Guideline No 19:2023 F



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Fire Safety | Security | Natural Hazards

The CFPA Europe develops and publishes common guidelines about fire safety, security, and natural hazards with the aim to achieve similar interpretation and to give examples of acceptable solutions, concepts, and models. The aim is to facilitate and support fire protection, security, and protection against natural hazards across Europe, and the whole world.

Today fire safety, security and protection against natural hazards form an integral part of a modern strategy for survival, sustainability, and competitiveness. Therefore, the market imposes new demands for quality.

These Guidelines are intended for all interested parties and the public. Interested parties includes plant owners, insurers, rescue services, consultants, safety companies and the like so that, in the course of their work, they may be able to help manage risk in society.

The Guidelines reflect best practice developed by the national members of CFPA Europe. Where these Guidelines and national requirements conflict, national requirements shall apply.

This Guideline has been compiled by the Guidelines Commission and is adopted by the members of CFPA Europe.

More information: www.cfpa-e.eu

Copenhagen, February 2023
CFPA Europe

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Cologne, February 2023
Guidelines Commission

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Key words:

1 Introduction

Saving human life is the most important objective in fire protection processes. Proper evacuation plans are essential to reach this objective. Two methods can be considered:

- The first is the prescriptive method, which deals with the occupancy, size and number of exits together with the maximum length of the escape routes;
- The second is the performance method, which deals with the maximum time limit for evacuation.

The first method is based on three main points:

- density of people;
- flow of people;
- length and width of evacuation routes.

The second method establishes if the required evacuation time is less than available safety egress time.

2 Scope

The main scope of this guideline is to supply valid support for the evacuation strategy to allow any kind of occupants, anywhere within the structure, to be able to evacuate to a place of safety.

3 Definitions

Actions: Actions, which may affect the compliance of the works with the essential requirements are brought about by agents acting on the works or parts of the works. Such agents include mechanical, chemical, biological, thermal and electro-magnetic agents.

Active fire protection measures: Systems and equipment installed to reduce danger to persons and property by detecting fire, extinguishing fire, removing smoke and hot gases, or any combination of these functions.

Alarm: Sudden attention or action for protection of persons or property (ISO 8201, 1987).

Critical conditions for occupants: Limit values for temperature increase, oxygen depletion and concentration of toxic combustion gases that seriously endanger life safety in a certain time.

Design fire scenario: A design fire scenario is a subsystem of all possible fire scenarios and represents the most probable or onerous of them. The Design fire scenarios are specific fire scenarios on which an analysis of performance will be conducted.

Emergency: Imminent risk of serious threat to person or property.

Escape route: Route forming part of the means of escape from any occupiable point in a building to a final exit.

Available safe egress time (ASET): Calculated time available between ignition of a fire and the time at which tenability criteria are exceeded in a specific space in a building.

Escape time: Calculated time from the ignition until the time at which all the occupants of a specified part of a building are able to reach place of safety.

Evacuation time: In relation to the orderly movement of persons to a place of safety in case of fire or other emergency, this is the interval between the time of a warning of fire being transmitted to the occupants and the time at which all of the occupants are able to reach a place of safety

Exit (fire emergency exit): Doorway or other suitable opening giving access towards a place of safety.

Exit signs: Signs which clearly indicate an exit.

Fire: A process of a not controlled combustion characterized by emission of heat accompanied by smoke and / or flame.

Fire alarm installation: Combination of components whose purpose is to give an audible and / or visible and / or other perceptible alarm of fire. The system may also initiate other ancillary actions.

Fire alarm, alarm of fire: Warning of a fire originated by a person or by an automatic device

Fire rescue team: Public or private organization with the aim of safeguarding life and fighting fires.

Fire compartment: An enclosed space in a building that is separated from other parts of the same building by enclosing construction having a specified period of fire resistance, within which a fire can be contained (or from which a fire can be excluded), without spreading to (or from) another part of the building.

Fire detector: Device, which gives a signal in response to certain physical and /or chemical changes accompanying a fire.

Fire door: A door or shutter, which, together with its frame and furniture as installed in a building, when closed is capable of meeting specified performance criteria concerning the resistance to fire.

Fire exposure: Thermal actions affecting the product.

Fire hazard: The potential to lose a life (or injury) and / or damage a property by fire.

Fire resistance: The ability of an element of a building construction to fulfil for a stated period of time the required load bearing function, integrity and / or thermal insulation specified in the standard fire resistance test.

Fire risk level: A function relating to the probability of fire causing a loss of life (or injury) and / or damage the property and the degree of harm caused.

Fire safety installations: Those installations concerning services, alarm and detection, installations for means of escape, suppression and firefighting equipment.

Fire scenario: A qualitative description of the course of a fire with time, identifying key events that characterize the fire and differentiate it from other possible fires It typically defines the ignition and fire growth process, the fully developed stage and the decay stage, together with the building environment and systems that will impact on the course of the fire.

Fire separating walls: A wall with a certain fire resistance, which separates two adjoining fire compartments.

Hazard analysis: Analysis carried out in order to evaluate the potential for loss of fire or injury and / or damage to the property.

Heat Release Rate: It is the rate, at which the combustion reactions produce heat. The expression "burning rate" or also "Rate of Heat Release" (RHR) is also often used. The heat release rate of a burning item is measured in kilowatts (kW).

Ignition: Initiation of combustion.

Movement time: The interval between the time when the occupants make the first move and the time when all of them are able to reach a place of safety.

Place of safety: A predetermined place in which persons are in no immediate danger from the effects of fire.
Note: The place of safety may be inside or outside the building depending upon the evacuation strategy.

Pre-movement time (Delay time to start evacuation movement): Time interval between the warning of fire, being given by an alarm or by direct sight of smoke or fire, and the first move being made towards an exit. This interval includes the perception of the alarm, the interpretation of the alarm, and the decision-making on how to proceed.

Required safety egress time (RSET): Calculated time required between ignition of the fire and the time at which the evacuation is completed and all occupants are in the place of safety.

Smoke: A visible suspension of solid and /or liquid particles in gases resulting from combustion.

Smoke control door: Door set designed to reduce the rate of spread or movement of smoke during the fire.

Tenability criteria: Maximum exposure to hazards from a fire that can be tolerated without causing incapacitation.

Travel distance: Actual distance that needs to be travelled by a person from any point within a building to the nearest exit, having regard to the layout of walls, partitions and fittings. In the calculation, fixed walls and fittings must be considered; movable furniture can be disregarded.

Travel time: Time needed once movement has begun, for all of the occupants of a specified part of a building to move to a place of safety.

Type of occupancy: Subdivision of occupancies as a function of the age, awareness and mobility of the occupants, the type of fire load, and kind of activity of occupancy.

4 Prescriptive approach to evacuation

The majority of building codes and fire safety standards used today are prescriptive.

Prescriptive codes find their roots in the 19th century when major conflagrations created the need for specific building provision.

These codes have been made without effectively evaluating their adequacy, excessiveness, or conflicts with other requirements. This has created codes based on empiricism and experience, rather than a scientific understanding of fire. Many advances in fire safety have been made, but they have not been incorporated into everyday fire safety practice.

The traditional basis of prescriptive life safety design is concentrated on physical requirements for means of escape. Prescriptive methods on the evaluation of evacuation safety are based on some or all of the following:

- minimum number of exits;
- minimum width of door and passages;
- maximum length of escape routes;
- maximum time for evacuation;
- managerial strategies to keep escape routes available and safe.

All prescriptive codes assume, explicitly or not, that the speed of occupants is assumed to be around 0.5 m/s and the time to escape about 3 -5 min. These values can be sufficient for the majority of the situations but in some cases, they can be insufficient. In these situations, an engineering approach is necessary.

5 Engineering approach: evaluation of safety conditions during evacuation

5.1 General

The performance method depends on the definition and comparison between the time available for occupants to reach a safe place, ASET (Available Safe Egress Time - the time at which tenability criteria are exceeded in a specific space) and the time occupants take to reach a safe place RSET (Required Safe Egress Time - it is the escape time).

The engineering approach requires a margin of safety, given by the difference between ASET and RSET time. This margin of safety may be useful for the uncertainties in the prediction of the two times.

$$T_{safety} = T_{ASET} - T_{RSET}$$

Performance method may be used in complex or singular buildings where a prescriptive approach could not be adequate. The engineering approach can also evaluate and validate the solutions of prescriptive methods.

5.2 ASET time quantification

5.2.1 General

ASET time quantification involves the ignition of fire and its spreading. It is the calculated time between the ignition of a fire and the time at which "tenability criteria" are exceeded because of smoke (decrease of visibility), toxic effluents and heat.

The endpoint of an ASET calculation is the time when conditions in each building enclosure are considered untenable.

Untenable conditions occur when it is predicted that an occupant inside or entering an enclosure is likely to be unable to save themselves (is effectively incapacitated) due to the effects of exposure to smoke, heat or toxic effluent.

ASET can also be limited by the effects of fire over the building construction, making the structure unstable and likely to collapse during the evacuation process, especially for unprotected, light steel structures.

The prediction of ASET requires estimation of the time-concentrations (or intensity) curves for the major toxic products, smoke and heat in a fire.

Information about physiological effects of exposure to fire is set out in Annex 1.

5.2.2 Fire scenario

Calculating ASET time depends on the nature of the fire, because combustion products give place to untenable conditions in the zone that is being evacuated.

The concentration and nature of the combustion products and their spread depend on the following factors:

- Chemical elements of substances involved in combustion;
- maximum temperature;
- oxygen concentration;
- ventilation.

In general, all these factors influence combustion.

To calculate ASET time, it is necessary to make a detailed study of the fire, from the ignition to its development.

All considerations to identify correctly the "Fire scenarios" and select the "Design fire scenarios" are given in ISO PTDS 16733-1 - Fire safety engineering – selection of design fire scenarios and design fires. Part 1: Selection of design fire scenarios.

In ISO 16733-1, "fire scenario" is a qualitative description of the course of a fire with respect to time identifying key events that characterize the studied fire and differentiate it from other possible fires. It typically defines the ignition and fire growth process, the fully developed stage, and decay stage as well as systems that impact on the course of the fire and the nature of the local environment.

5.2.3 Design fire scenario

To characterize fire scenarios, logical process to be followed may be summarized into three points:

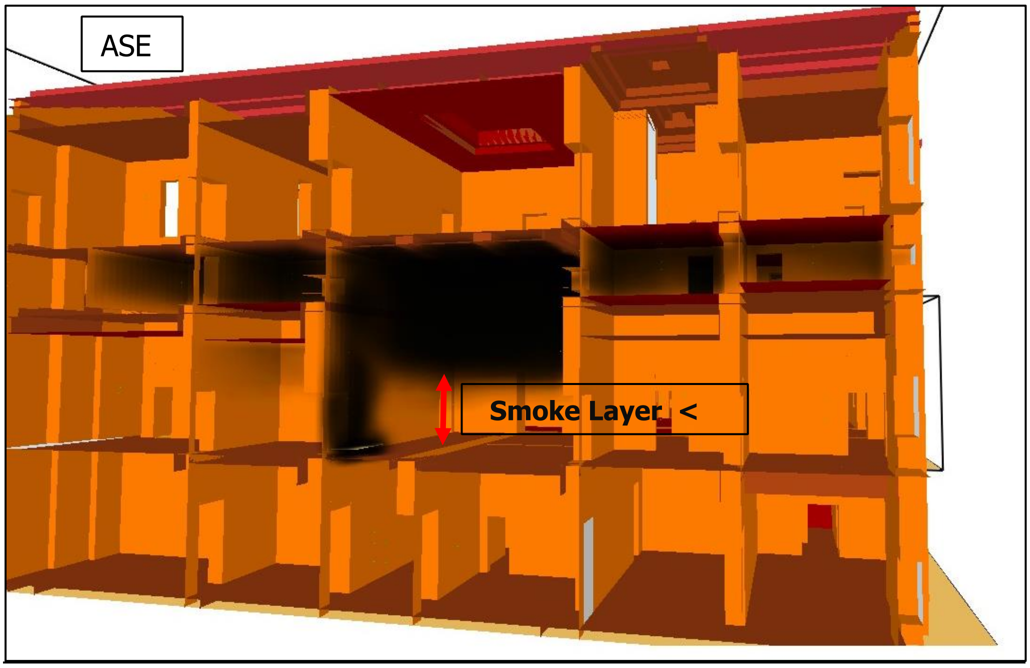
- Taking into consideration all possible fire scenarios;
- among all possible fire scenarios, choosing one (or, more often, some of them) that are considered as the most probable and onerous. They are the Design fire scenarios;
- for the chosen design fire scenarios, calculating the quantitative levels of all the factors that influence egress (e.g. smoke, visibility, heat, etc.).

Normally the number of possible fire scenarios is quite high. For this reason, their number is normally reduced using design fire scenarios.

Some information about the definition of fire scenarios and individuation of design fire scenarios is included in Annex 2.

5.2.4 Calculation of design fire scenarios

A design fire is characterized from the fire growth depending on the nature (not the quantity) of the materials contained in the building; the fire growth could be defined by the actual HRR history of the products or it could be a generalized HRR history of a product category. The definition of HRR represents the "identity card" of the fire and is the necessary factor to both calculate the rate of smoke production and the input parameters for fire simulation software.



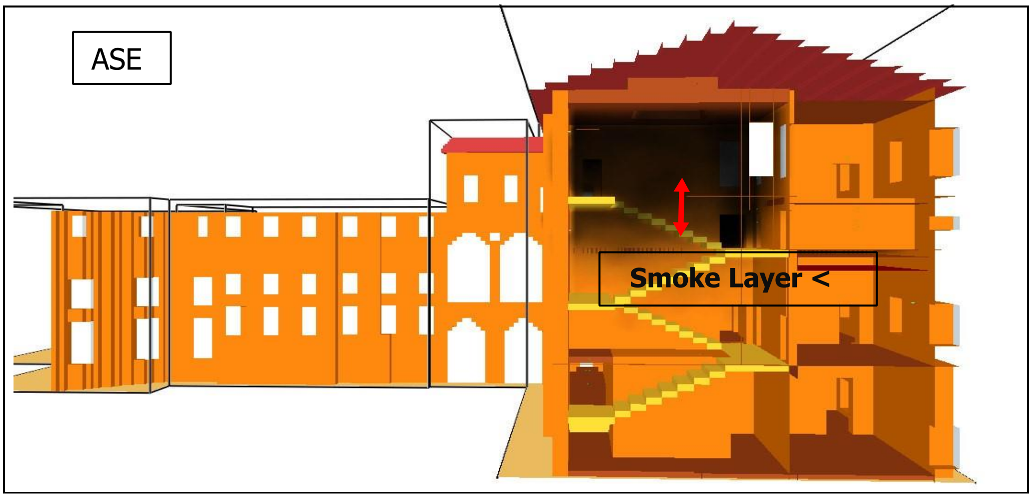


Figure 1a: Example FDS output

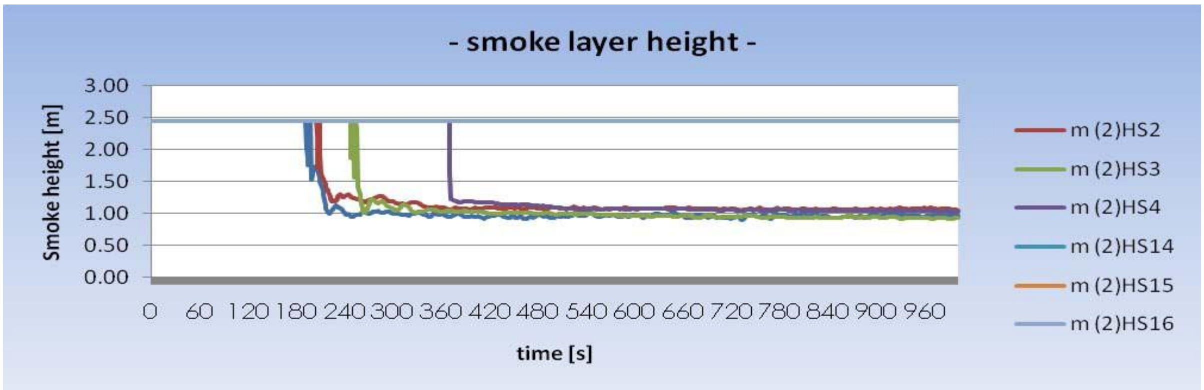


Figure 1b: Example FDS output

The calculations of design fire scenarios using a fire simulation model have the principal aim to calculate the evolution along time and space of fire effluents, the concentrations of toxic gases and the temperature of smoke. These parameters are compared with the tenability criteria chosen for the ASET calculation.

Some considerations about the main software programs for simulating fire scenarios are included in Annex 3.

5.3 RSET time quantification

Escape time in safe conditions (RSET, Required Safe Egress Time) depends on four different "times", influenced by occupants' physical and behavioural characteristics. The four times are:

Detection time: The time from the beginning of ignition to its detection by a manual or automatic system. It may vary according to the fire scenario, the fire detection system (if in place) and the ability that occupants have to detect the fire.

Alarm time: The time from the detection to triggering a general alarm.

Pre-movement time: The time from detection to the moment, the first occupant starts moving; Places where occupants can be asleep (e.g. hotels) must consider a higher pre-movement time. Specific training on how to behave in case of emergency will provide shorter pre-movement times.

Travel time: the time occupants take to move from where they are to a safer place. It has two sub-components:

- **Walking time:** The time occupants take to walk to the exit. It may be expressed as a distribution of individual times or as a single time, as to say, the average time required to walk to the exit or the time the last occupant need to walk to the exit. Walking time depends on the walking speed of each occupant, their distance from the exit, physical dimensions of the building and the distribution of the occupants;
- **Flow time:** The time occupants take to flow through exits and escape routes. Flow time depends on the flow capacity of the exit and the number of people using that particular exit.

$t_{RSET} = t_{\det} + t_a + (t_{pre} + t_{trav})$

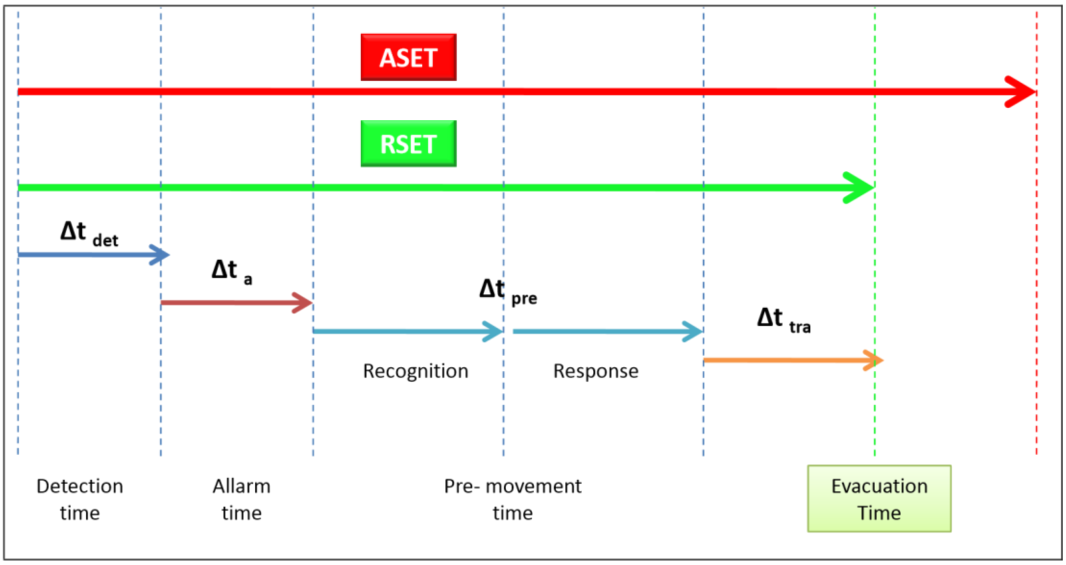


Figure 2: RSET

The four times are strongly influenced by human behaviour, for this reason it is not easy to give them an exact value. For the analysis, occupant's behaviours in real and simulated emergencies have been observed.

Some information about the definition of these times is included in Annex 3.

5.4 Conclusion

For a safe evacuation, the precise design of escape routes in relation to the distance to a place of safety and to the evacuation time has a crucial importance, therefore we have to pay attention and consideration to all the opportunities provided by the development of the Fire Safety sciences.

The choice of the most suitable approach and calculation methods for a correct evacuation design belong to the engineer, and can rely on different tools, from the most simple manual calculation to the most sophisticated simulation software, depending on the objective and the level of accuracy intended.

Annex 1 Physiological effects of exposure to fire Inspection checklist

ASET time depends proportionately to the effects of exposure to fire on people. Briefly, the following are most common physiological effects[1]:

Annex 1.1 Effects due to radiative heat

- Hyperthermia
- Body surface burns, caused by radiant heat and smoke.
- Respiratory tract burns, caused by hot gases and smoke.

Heat is dangerous for people because it may cause dehydration, breathing difficulties, asphyxia and burns.

The tenable limit of air temperature is about 150 °C. The exposure needs to be very short and the air dry.

The temperature is lower if the air is wet. Unfortunately, in case of a fire, water vapour content is quite high. Air temperature tenable limit for a short time is about 60°C.

Mode of heat transfer	Intensity	Tolerance time
Radiation	< 2,5 KW/m^2	> 5 min
	2,5 KW/m^2	30 s
	10 KW/m^2	4 s
Convection	<60 °C 100% saturated	> 30 min
	100 °C < 10% H_2O	8 min
	110 °C < 10% H_2O	6 min
	120 °C < 10% H_2O	4 min
	130 °C < 10% H_2O	3 min
	150 °C < 10% H_2O	2 min
	180 °C < 10% H_2O	1 min

Table 1: Tenability limits for a radiative and convective heat[2]

Annex 1.2 Effects due to the production of combustion gases

- Visibility reduction
  and
- irritancy to eyes and respiratory tract

cause inability to escape

Ability to escape through building spaces and ability to locate escape routes and exits depends upon the effects of irritancy and visual obscuration.

[1] Detailed guidance on estimation of the effects of individual asphyxiating gases and the interactions between them are given in BS 7899-2

[2] Source: PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition"

"Visibility" distance is a very important element. Decreasing visibility distance decreases the possibility to find a safe place.

Occupants are likely not to use an exit if the visibility distance is less than approximately 3m. Irritant smoke causes a reduction of visibility and flow speed.

Irritants in fire effluent consist of a range of organic compounds, including acrolein and formaldehyde, which are likely to be present in any fire effluent atmosphere at concentrations depending upon the chemical composition of the fuel and the fire decomposition conditions.

Annex 1.3 Asphyxia/toxicity

Even if fuel gases get colder and room temperature decreases to 15°C, they continue to be gases. Most common fuel gases are:

Carbon monoxide (CO)	Hydrocyanic acid (HCN)
Carbon dioxide (CO_2)	Hydrochloric acid (HCl)
Hydrogen sulphide (H_2S)	Nitrogen peroxide (NO_2)
Sulphurous anhydride (SO_2)	Acrylic aldehyde (CH_2CHCHO)
Ammonia (NH_3)	Phosgene ($COCl_2$)

Table 2: Most common fuel gases

Carbon monoxide

Carbon monoxide develops from fires breaking out in enclosed spaces and in oxygen shortage. Characteristics:

- Colorless;
- odorless;
- not irritating.

During fires, it is the most dangerous toxic gas because it is highly toxic, it is usually produced in high quantity and people normally cannot be aware of breathing it.

Carbon dioxide

Carbon dioxide is an asphyxiate gas. It is not toxic, but during a fire it displaces the oxygen. When oxygen levels decrease to rates lower than 17% per volume, carbon dioxide causes asphyxia.
It quickens and stimulates breathing. Having just 2% of CO_2, breathing speeding and deepness increases 50% comparing to normal conditions. Having 3% of CO_2, breathing speed and deepness doubles (100%).

Hydrocyanic acid

Hydrocyanic acid develops in small quantities from ordinary fires, after an incomplete combustion (oxygen shortage) of wool, silk, acrylic, polyamide and urethane resins. It has the characteristic smell of bitter almonds.

Hydrocyanic acid stops the respiratory chain, disabling tissues, which need a high level of oxygen (heart, nervous system) to function.

Phosgene
Phosgene is a toxic gas developed from combustion of materials with chlorine (plastic materials). It is very dangerous in enclosed spaces. Entering in contact with water or humidity, phosgene splits into carbon dioxide and hydrochloric acid. Hydrochloric acid is very dangerous because it is extremely acidic and able to reach respiratory tracts.

Reference value is **I.D.H.L: "Immediately Dangerous to Life and Health"**: The lower concentration of contaminants that is likely to cause death, or immediate or delayed permanent adverse health effects, or prevent escape from such an environment.

Substance	Formula	I.D.H.L. (ppm)
Carbon monoxide	CO	1200
Carbon dioxide	CO_2	40000
Hydrocyanic acid	HCN	50
Ammonia	NH_3	300
Hydrochloric acid	HCL	50

Table 3: Most common combustion products I.D.H.L. values

IDHL values for other contaminants can be found at National Institute for Occupational Safety & Health (NIOSH), Centers for Desease Control and Prevention (CDC)[3]. The maximum concentration values, which are commonly used as acceptance criteria in Performance Based Design are quite lower than those given in table 3. For example, for the most common toxic gases (CO and CO_2), the acceptance criteria for CO use to be around 150 ppm, and for CO_2 use to be around 3% (30.000 ppm).

Annex 1.4 Effect due to the reduction of oxygen concentration
During combustion, the oxygen level decreases and fuel gases are produced. Oxygen decrease is very dangerous: at rest, people need 10l/min of oxygen in about 20 inspirations of 0,5l each; every inspiration having 16% of oxygen concentration. A person shows serious symptoms if the concentration of oxygen is lower than 14%.

Annex 2 Definitions and characteristics of fire scenarios

Annex 2.1 Definition of fire scenarios
As far as the definition of the fire scenarios is concerned, it is essential to identify and retrieve all the information that can contribute to the possibility that a fire could start, on the way that it could be caused and spread. In addition, information concerning the potential possibility of causing harm to the occupants, building structures and their contents.

For each scenario three characteristics should be defined:

[3] See: www.cdc.gov/niosh/

- Characteristics of the fire;
- characteristics of the building;
- characteristics of the occupants.

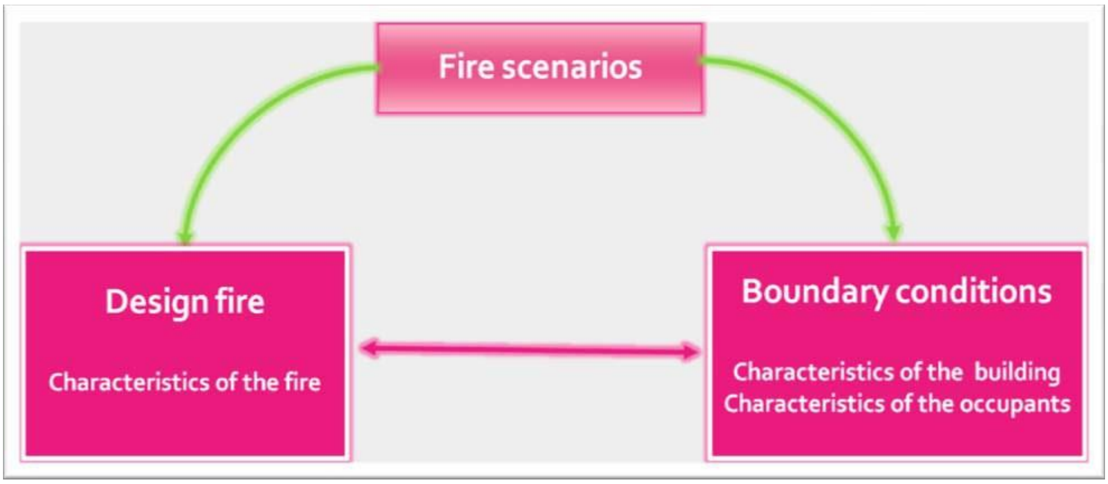


Figure 3: Fire scenarios

Characteristics of the fire
The main aspect to be considered are:

- Nature of combustibles;
- geometric arrangement of the fuel;
- geometry of the enclosure;
- ignitability of the fuel;
- rate of heat release characteristics;
- ventilation, state of doors and windows (open or closed). Period of time during which fire may develop when doors may be open or closed;
- external heat flux;
- exposed surface area;
- extinguishing systems.

The characteristics of the type of fuel (quantity, type, ignition timing and sequence) and the ventilation conditions (geometric enclosure characteristics) are essential to determine the heat release rate during the fire. This definition represents the "identity card" of the fire and is the necessary element in order to both calculate the rate of smoke production and the input parameters for fire simulation software.

A full specification of a design fire through heat release rate includes the following phases:

- Incipient phase — characterized by a variety of sources, which may be smouldering, flaming or radiant;
- growth phase — covering the fire propagation period up to flashover or full fuel involvement;
- fully developed phase — characterized by a substantially steady burning rate as may occur in ventilation or fuel-bed-controlled fires;
- decay phase — covering the period of declining fire severity;
- extinction — when there is no more energy being produced.

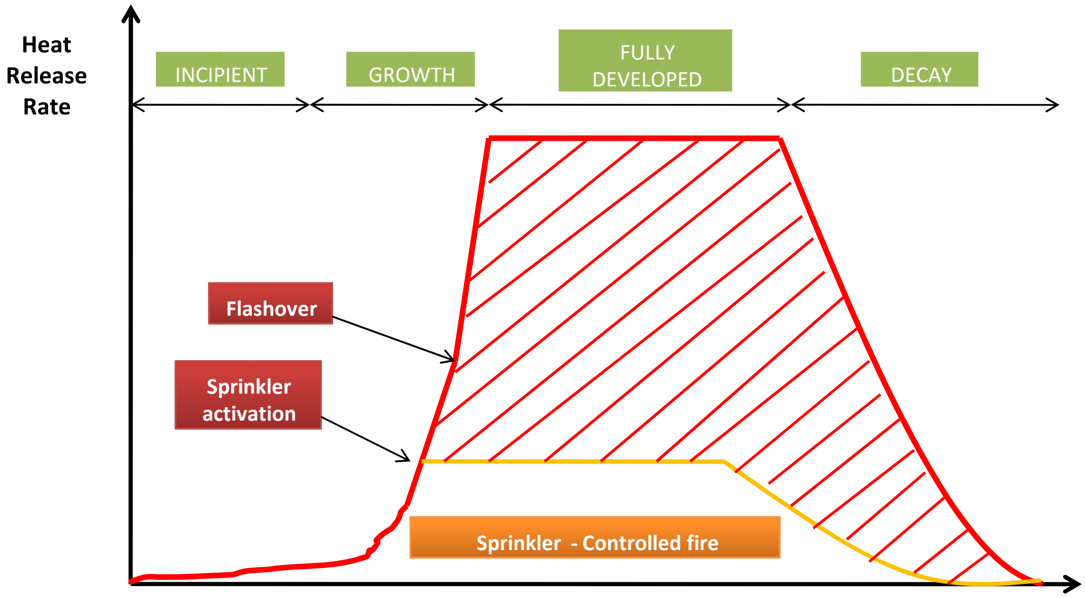


Figure 4: Typical Heat release rate

Characteristics of the building
When a fire scenario occurs, the characteristics of the building must be detailed with a full description of its physical nature, its contents and the environmental conditions. This will influence the evacuation of the occupants, the growth and development of the fire as well as the movement and diffusion of the fuel.

Generally the following characteristics are taken into consideration:

- Architectural characteristics (height, width, enclosures);
- structural characteristics;
- presence of fire detection protection systems, active and passive (working or not);
- purpose of the building;
- time of response of internal fire emergency teams;
- environmental factors;
- presence of natural and/or mechanical ventilation.

Characteristics of the occupants
In order to determine the capability of response to evacuation of the occupants during emergency, the characteristics of the occupants must be defined. Generally the following is taken into consideration:

- Number of occupants;
- distribution in the building;
- alertness (asleep or awake);
- specific or special purpose (hospitals, prisons , etc.);
- focal points;
- physical capability and all possible disabilities, sensorial and mental[4];
- familiarity with the environment;
- physical and psychological conditions;

[4] Please see CFPA-E Guideline No. 33, "Evacuation of people with disabilities"

- specific training on how to behave in case of emergency and conduction of emergency drills.

The factors concerning the characteristics of the occupants, essential aspect for the evaluation of a safe evacuation shall be discussed in more detail in the paragraphs dealing with the calculation of the RSET.

Annex 2.2 Characteristics of design fire scenariosU

By means of the information gathered before, it is possible to assume the most serious scenario which could reasonably or probably occur in the event of fire.
Once all these aspects are determined and are taken into consideration by experts, or by means of analysis of probability a sub-group of the fire scenario project is defined.
The number of possible design scenarios is quite high. For this reason, their number is normally reduced using design fire scenarios, following two different ways:

- **Probabilistic way:** Is based on the probability that a fire may break out. It studies the U possible consequences. This method is used by industry, where data on probable damages, components and equipment characteristics are more reliable. Methods used are: Hazop, FMEA, Fault tree analysis and Event tree analysis. Probabilistic methods are hardly used by civil engineering, because of the lack of significant statistical data.
- **Expert judgments:** According to this method, the most serious fires are assumed to U happen. This is the way mostly used by civil engineering, even if it is quite hard finding a number of fire scenarios, which are sufficiently different one from the others. The expert judgement way does not need to know the fire frequency.

The following is an alternative method, which refers to NFPA 101 (Life safety code): In this method, the code suggests 8 fire scenarios. A limit of the method is the high number of analytical calculations it needs to cover the different scenarios hypothesis. Another limit is the seriousness of supposed scenarios. For example: estimation of what may happen if exits are blocked by burning materials, or building estimation when a protection system doesn't work.

It is necessary to mention ISO 16733-1 "Fire safety engineering — Selection of design fire scenarios and design fires" because it suggests a method to identify and select design fire scenarios based on the following points:

Identification of fire scenarios:

- Identify the specific safety challenges;
- location of fire;
- type of fire: The most likely type of fire scenario can be determined from consideration of the items most commonly ignited, the ignition source and location of the fire from relevant fire incident statistics;
- potential fire hazards;
- systems impacting on fire;
- occupant actions impacting on fire.

Selection of fire scenarios:

- Combining scenarios into scenario clusters;
- caution on exclusion of scenarios believed to have negligible risk;
- demonstrating that the scenario structure is complete;
- scenario selection procedure based on level of analysis;
- selection of design fire scenarios for deterministic analysis;
- modify scenario selection based on system availability and reliability;

- final selection and documentation.

Typically, it is an idealized description of the variation with time of important fire variables such as heat release rate, fire spread, smoke and toxic combustion gases, and temperature. The analysis of the evolution of these parameters are basic to define the ASET.

When evaluating a safe evacuation all the characteristics of the fire, the building and its occupants likely to cause a critical evacuation, are taken into consideration. For example:

- Detail of fuel (development speed and toxic/suffocating gasses);
- fire location in places where it is difficult to control or near emergency exits;
- sleeping occupants.

Once the project design fire scenario has been selected, all the all the relevant information (characteristics of the fire and details of enclosure where it has developed) is put together with formulas, statistics and fire simulation modules, in order to determine ASET based on the evolution of different parameters.

The knowledge of these parameters, concerning time, allows us to establish the exact moment in which the conditions of the environment do not guarantee the possibility to evacuate in safe conditions. (ASET TIME).

The procedure to establish the ASET time is highly specialized and an expert knowledge of the chemical and physical properties of the substances is required, to be able to use these results during the output supplied by software, especially in the case of toxic substances.

The PD 7974-6:2019 "Human factors: Life safety strategies – Occupant evacuation, behaviour and condition", because of the difficulties to optimize the necessary information concerning the calculation of the toxic concentrates, recommends a conservative approach based on the "no exposure" concept. This concept suggests to refer to, as per ASET time, the time that hot smoke at ceiling height takes to reach 2,5 m from the floor along the exit ways. When the temperature at ceiling height does not reach 200°C heat radiation is in general still bearable at circulation level and the occupants are able to evacuate in a space with air, which is still clean.

Fire modelling software provides an easy way to calculate the smoke height and temperature and the concentration of toxic gases.

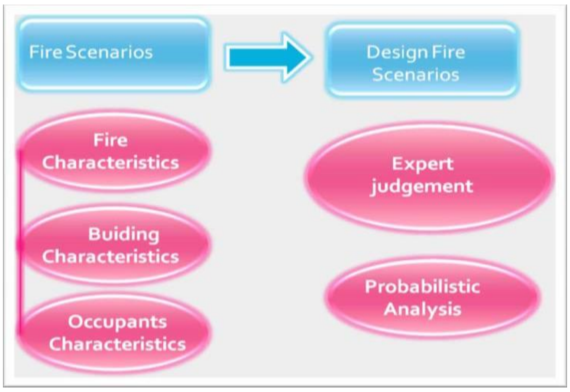


Figure 5: Fire Scenarios and Design Fire Scenarios

Annex 3 Considerations about the main Computational Fluid Dynamics (CFD) models

Feature from "An Updated International Survey of Computer Models for Fire and Smoke" - STEPHEN M. OLENICK* AND DOUGLAS J. – CARPENTER, Journal of FIRE PROTECTION ENGINEERING, Vol. 13—May 2003:

The principal aim of this Annex is to show the most common type of fire model giving a short description of two types. The categories chosen for computer fire models include zone models and field models.

Annex 3.1 Zone Models:

A zone model is a computer program that predicts the effects of the development of a fire inside a relatively enclosed volume. In most applications, the volume is not totally enclosed as doors, windows, and vents are usually included in the calculation. Zone models for compartments have been developed for both single-room and multi-room configurations. The 'zonal' approach theory to modelling plume and layer development in confined spaces was applied to fires by several groups in the 1970s, e.g. Zukoski.

The 'zonal' approach divides the area of interest into a number of uniform zones, that when combined, describe the area of interest as a whole. Within each of these zones, the pertinent conservation laws (i.e. mass and energy), in the form of mathematical equations describing the conditions of interest, are solved. The 'zonal' approach for an enclosure fire usually divides an enclosure into two distinct zones: the hot upper smoke layer and the lower layer of cooler air. The plume acts as an enthalpy pump between the lower layer and the hot upper smoke layer.

In reality, depending on the room size and heat release rate of the fire, there is no perfectly defined 'interface' between the hot upper smoke layer and lower layer. The hot upper smoke layer is not an uniform temperature (as higher temperatures are observed closer to the fire and plume); however, the use of two uniform zones allows for reasonable approximations of the development of a fire in an enclosure under many conditions. Table 4 lists some of the zone models which have been identified.

Model	Country	Description
ARGOS	DENMARK	Multi-compartment zone model
ASET	US	One room zone model with no ventilation
ASET-B	US	ASET in Basic instead of Fortran
BRANZFIRE	NEW ZEALAND	Multi-room zone model, including flame spread, multiple fires, and mechanical ventilation
BRI-2	JAPAN/US	Two-layer zone model for multistory, multi-compartment smoke transport
CALTECH		Pre-flashover zone model
CCFM.VENTS	US	Multi-room zone model with ventilation
CFAST/FAST	US	Zone model with a suite of correlation programs-CFAST is the solver, FAST is a front-end
CFIRE-X	GERMANY	Zone model for compartment fires, particularly liquid hydrocarbon pool fires
CiFi	FRANCE	Multi-room zone model
COMPBRN-III	US	Compartment zone model
COMF2	US	Single room post-flashover compartment model
DACFIR-3	US	Zone model for an aircraft cabin
DSLAYV	SWEDEN	Single compartment zone model
FASTlite	US	Feature limited version of CFAST
FFM	US	Pre-flashover zone model
FIGARO-II	GERMANY	Zone model for determining unitability
FIRAC	US	Uses FIRIN, includes complex vent systems
FireMD	US	One room, two zone model
FIREWIND	AUSTRALIA	Multi-room zone model with several smaller sub-models (update of FIRECALC)
FIRIN	US	Multi-room zone model with ducts, fans, and filters
FIRM	US	Two zone, single compartment model
FIRST	US	One room zone model, includes ventilation
FMD	US	Zone fire model for atria
HarvardMarkVI	US	Earlier version of FIRST
HEMFAST	US	Furniture fire in a room
HYSLAV	SWEDEN	Pre-flashover zone model

Table 4: Fire Zone Models

Annex 3.2 Field Models

Field models, like zone models, are used to model fire development inside a compartment or a series of compartments. While a zone model divides the compartment into two zones, and solves the conservation equations (i.e., mass, energy, and momentum) within these zones, a field model divides the compartment into a large number (on the order of thousands) of control volumes and solves the conservation equations inside each control volume. This allows for a more detailed solution compared to zone models. Because there are more than two uniform zones, a field model can be appropriate for geometries, that are more complex, where two zones do not accurately describe the fire phenomenon. They can also be used for fires outside of compartments such as large outdoor fuel tank fires. While field models provide very detailed solutions, they require detailed input information, and usually require more computing resources in order to model the fire. This can create a costly time delay in obtaining a solution while zone models usually provide a solution more quickly. This trend of increasingly growing numbers of field models stems from improved computer hardware, which allows for faster, more complex computational techniques. Table 5 lists some of the field models, which have been identified.

Model	Country	Description
ALOFT-FT	US	Smoke movement from large outdoor fires
CFX	UK	General purpose CFD software, applicable to fire and explosions
FDS	US	Low Mach number CFD code specific to fire-related flows
FIRE	AUSTRALIA	CFD model with water sprays and coupled to solid/liquid phase fuel to predict burning rate and extinguishment
FLUENT	US	General purpose CFD software
JASMINE	UK	Field model for predicting consequences of fire to evaluate design issues (based on PHOENICS)
KAMELEON FireEx	NORWAY	CFD model for fire linked to a finite element code for thermal response of structures
KOBRA-3D	GERMANY	CFD for smoke spread and heat transfer in complex geometries
MEFE	PORTUGAL	CFD model for one or two compartments, includes time-response of thermocouples
PHOENICS	UK	Multipurpose CFD code
RMFIRE	CANADA	Two-dimensional field model for the transient calculation of smoke movement in room fires
SMARTFIRE	UK	Fire field model
SOFIE	UK/SWEDEN	Fire field model
SOLVENT	US	CFD model for smoke and heat transport in a tunnel
SPLASH	UK	Field model describing interaction of sprinkler sprays with fire gases
STAR-CD	UK	General purpose CFD software
UNDSAFE	US/JAPAN	Fire field model for use in open spaces, or in enclosures

Table 5: Fire field models

Annex 4 Calculation of RSET time

As explained in chapter 5.3, RSET time is the sum of four different times. Following paragraphs will explain each time, giving information taken from literature.

Annex 4.1 Detection Time

In an automatic detection system, detection time depends on the sensitivity of the system. Automatic system planners calculate the detection time. Lacking an automatic detection system, detection time is estimated basing on the planned fire scenario. The following are the characteristics of a fire scenario, which may cause a delay on fire detection:

- Occupants characteristics: sensory skills and activities they are involved in;
- building characteristics;
- fire characteristics: speed of spreading, smoke, etc.

Annex 4.2 Alarm Time

Guidance on estimation of alarm time is provided in PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition". It reports three different alarm levels:

Level A1: The building is provided with an automatic fire system. Once the fire has been detected, the system immediately activates the alarm throughout the all building. The time from the detection to the general alarm is zero.

Level A2: In this case the building is provided with an automatic fire system but the general alarm is not immediate. A pre-alarm is transferred to the safety room (pre-alarm system). In this case, the pre-alarm time depends on the safety management strategy. In any case, pre-alarm time should go from 2 to 5 minutes. Safety management evaluation allows a more exact range definition.

Level A3: A manually activated alarm system is located near the source of the fire. In this case, a range time definition is very far from being exact because it depends on fire scenario and occupants characteristics: age, role and responsibility in the building, training in case of fire. When planning an alarm system, it is important to take into consideration the building structure:

- In a small single storey building, it is necessary to sound an immediate general alarm throughout the building (Level 1);
- in a big multi-storey crowded building, it is advisable to have a staged fire alarm system: first the warning system in the floor affected is activated, then the warning system in the floor upstairs so as not to have a simultaneous evacuation and congestion at the exits.

Annex 4.3 Pre-movement Time

This may be sub-divided into two components:

Recognition: The time from the general alarm to the time occupants, begin to respond. It may be divided into two elements:

- Alarm receiving: time used to receive the alarm from the acoustic/visual alarm devices;
- alarm processing: time to understand and process that the alarm of cue received is an evacuation warning.

During the recognition time, occupants continue with the activities they were engaged with before the alarm.

The recognition time ends when occupants decide to take some action in response to the emergency signals received.

For simple evaluations, the average or the slowest recognition time may be taken for each group of occupants. For complex evaluations, recognition time may be assigned to each individual.

The following are suggestions to minimize recognition time:

- The system should provide precise instructions under varying emergency situations;
- instructions should be capable of varying in the different parts of the buildings so as to provide occupants with the information tailored upon the actions they are desired to take;
- alerting tones should precede voice instructions to capture occupants attention;
- pre-recorded messages may be used in pre-planned situations;
- in health care occupancies, where the staffs are trained to notify and assist occupants with evacuation, it is advisable to alert just those individuals who need to take action, to have a maximum life safety benefit from a fire alarm system. Others can be notified, but not alerted.

Response: It´s defined as the elapsed time from the alarm recognition to the moment occupants decide to respond, but before beginning the evacuation.

Examples of activities undertaken during the response time:

- Investigative behaviour, including action to determine the source, reality or importance of a fire alarm or cue;
- stopping machinery/production processes or securing money and other risks;
- seeking and gathering together children and other family members;
- fighting the fire;
- the time involved in determining the appropriate exit route (i.e. "wayfinding"); and the time involved in other activities not fully contributing to effective evacuation where necessary (for example acting on incorrect or misleading information);
- alerting others.

Pre-movement time may vary considerably for different individuals or groups of individuals located within the same enclosure or in different enclosures.

Elements to be taken into consideration to estimate recognition and response time are as follows:

Building parameters:

- Occupancy type;
- floor plans, layout and dimensions;
- contents;
- warning system;
- fire safety management emergency procedures;
- signs;
- lighting;
- location of exits and complexity of enclosure layout.

Occupant status:

- Number and starting location of occupants: The occupant density of a U room is the maximum number of persons anticipated to be present for a given configuration or use. Where there is no other information available, the number should be estimated according to use, for example dividing the area of the room or the story by an appropriate occupant density factor. Potential changes in occupancy density data need to be considered. Conservative design requires use of the maximum potential occupant density. Designers should be mindful that the numbers and distribution of occupants in a building will change with the time and the activity;
- characteristics of the occupants: Gender, age; gender implies differences between the size of male and female bodies. This is considered when stating the flow through doors, aisles, and stairs. Age influences both the capability people have to recognize an alarm and their quickness in acting. Old and young people find more difficult recognizing an alarm, but once young people have decided to move, they are quick and strong to face smoke and heat. Old people and children have difficulties in evacuating without assistance;
- activities of the occupants before the emergency;
- family or group relationships: Response to alarms or fire cues is affected by U whether people are alone or with others. The presence of other people can have an inhibiting effect on the definition and initiation of action from initial ambiguous alarms. They are likely first to attempt to re-establish the group. People who are alone tend to respond more rapidly to ambiguous cues. In addition, the speed of movement will often be dictated by that of the slowest member of the group;
- occupant condition / physical and mental ability: A proportion of the population may be impaired (cognitively and/or physically) or will present some level of limitation related to injury, illness poor health, age, weight, or other conditions. The initial response of disabled people may involve a considerable preparation time before moving. Their movement is significantly influenced by the nature of their disability and building elements such as doors, ramps and stairs. People with a hearing disability may require special means of notification of a fire, although their evacuation movement may not be different from mobile occupants. People with a visual disability may perceive audible information such as a fire alarm or a voice communication message but might need assistance to find a suitable evacuation route;
- alertness: Depends on factors such as activities, time of day, sleeping or awake;
- role and responsibility: The rules and responsibilities of occupants during the U normal use of the building will, in an emergency, influence their behaviour and the behaviour of the others. Sufficient, well trained, and authoritative staff will shorten the ambiguous, information-gathering phase of pre-movement time.

The analysis of all these elements allows the recognition and response time evaluation for each occupant or for group of occupant per enclosure.

Quantification of Pre-movement time: The pre-movement time is given by the time elapsed from the communication of an alarm to the first movement of an occupant, including recognition and processing of the alarm. The pre-movement time is different for every occupant, following a normal log distribution: the number of people starting moving increases rapidly and they form a very long queue.

That is why there are two times to take into consideration: the first occupant’s pre-movement time (i.e. 1st percentile) and the last occupant’s pre-movement time (i.e. 99th percentile).

In PD 7974-6:2019 "Human factors: Life safety strategies – Occupant evacuation, behaviour and condition", a table analyses the two pre-movement times and the so called "behavioural scenarios".

Behavioural scenarios summarize the elements used to define recognition and response time. The table is useful to give a value to recognition and response time.

PD 7974-6:2019 refers four elements to define behavioural scenarios:

- Occupancy type;
- alarm system;
- building complexity;
- safety management system.

Occupancy type:

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

Table 6: Occupant category[5]

Alarm system:
Level A1: An automatic detection system, which gives a general alarm throughout the building.

Level A2: An automatic detection system, which doesn't give an immediate general alarm but transfers a pre-alarm to the security room (pre-alarm system).

Level A3: a manually activated alarm system near the affected area.

Building level:
BUILDING LEVEL B1: (e.g. simple supermarket) represents a simple rectangular single storey building with one or few enclosures and a simple layout with good visual access, prescriptively designed with short travel distance, and a good level of exit provision with exits leading directly to the outside of the building.

[5] Source: PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation behaviour and condition"

BUILDING LEVEL B2: (e.g. simple multi-storey office block of less than 60 m storey height) represents a simple multi-enclosure building, with most features prescriptively designed and simple internal layouts.

BUILDING LEVEL B3: Represents a large complex building. This includes large building complexes with integration of a number of existing buildings on the same site, common with old hotel or department stores, also large modern complexes such as leisure centres, shopping centres and airports. Important features are that internal layout and enclosures involve often large and complex spaces so that occupants may be presented with wayfinding difficulties during an evacuation and the management of an evacuation therefore presents particular challenges.

Management level:
MANAGEMENT LEVEL M1: The normal occupants (staff or residents) should be trained to a high level of fire safety management with good fire prevention and maintenance practice. For "awake and unfamiliar, there should be a high ratio of trained staff to visitors. The system and procedures are subject to independent certification, including a regular audit with monitored evacuations for which the performance must match the assumed design performance. This level would usually also imply a well-designed building with obvious and easy to use escape route (to level B1 or at least B2), with automatic detection and alarm systems to high level of provision (level A1).

MANAGEMENT LEVEL M2: Similar to level 1, but have a lover staff ratio and floor wardens may not always be present. There may be no independent audit. Building features may be level B2 or B3 and alarm level A2. The design escape and evacuation times will be more conservative than for a level M1 system.

MANAGEMENT LEVEL M3: Representing standard facilities with basic minimum fire safety management. There is not independent audit. The building may be level B3 and alarm system A3. This is not suitable for a fire-engineered design unless other measures are taken to ensure safety.

A good guide for fire safety management is BS 5588-12.

Having once found the behavioural scenario close to the occupants' situation, the following table from PD 7974-6:2019 may be observed to have a rough estimate of pre-movement time. Specifically, the table 7 gives the 1st percentile and 99th percentile pre-movement times.

Scenario category and modifier	First occupants	Occupant distribution
	$\Delta t_{pre(1st\ percentile)}$ A)	$\Delta t_{pre(99th\ percentile)}$ B)
A: awake and familiar		
M1 B1 – B2 A1 – A2	0.5	1.5
M2 B1 – B2 A1 – A2	1	3
M3 B1 – B2 A1 – A3	*>15*	*>30*
For B3, add 0.5 for wayfinding		
M1 would normally require voice alarm/PA if unfamiliar visitors likely to be present		
B: awake and unfamiliar		
M1 B1 A1 – A2	0.5	2.5
M2 B1 A1 – A2	1.0	4.0
M3 B1 A1 – A3	*>15*	*>30*
For B2, add 0.5 for wayfinding		
For B3, add 1.0 for wayfinding		
M1 would normally require voice alarm/PA		
Ci: sleeping and familiar (e.g. dwellings – individual occupancy)		
M2 B1 A1	*5*	*10*
M3 B1 A3	*10*	*>40*
For other units in a block assume one hour		
Cii: managed occupancy (e.g. serviced apartments, halls of residence)		
M1 B2 A1 – A2	*10*	*30*
M2 B2 A1 – A2	*15*	40
M3 B2 A1 – A3	*>20*	*>40*

Table 7: Pre-movement times[6]

Once given a value to the pre-movement time using the tables, PD 7974-6:2019 suggests to simplify the complex analysis of evacuation time, considering each occupant position, pre movement time, walking time and the effects occupants density have on walking time (subject analysed in the following paragraph), just using two estimations. It may be used for any building enclosure, considering two simple cases:

- A case where the enclosure is sparsely populated with a density population of 1/3 of the design population;
- a case where the enclosure contains the maximum design population.

For both cases, the largest exit should be disregarded.

In the first case, evacuation time depends on the pre-movement time of the last group of occupants deciding to leave and on the time, they take to travel to the exit and walk through. As long as

[6]Source: PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition"

occupants' density is low, their walking speed will not be impeded and there will not be queuing at the exits.

$t_{RSET} = t_{det} + t_a + (t_{pre}(99^{th}\ percentile) + t_{trav}(walking))$

In the second case, evacuation or RSET time depends on the pre-movement time and walking time of the first group of occupants deciding to evacuate (1st percentile) plus the flow time through the exits where queues are likely to be formed.

$t_{RSET} = t_{det} + t_a + (t_{pre}(1^{st}\ percentile) + t_{trav}(walking) + t_{trav(flow)})$

It has to be done a conservative estimation of the walking time using the maximum direct travel distance to the exit. Assuming unrestricted moving speed (not conditioned by occupants' density) is likely to have a negligible effect on the calculated total evacuation time.

The longer time obtained should be used for design purposes. In most scenarios, the second case will represent the longest required escape time.

When the evacuation involves simultaneous evacuations from many enclosures into an escape route (corridor or stairs), evacuation time depends on the flow capacity of the escape route where flows from different enclosures merge. In this case, hand calculation cannot be carried out simply, for this reason it is advisable to use computer simulation models.

The flow rate of occupants from individual enclosures depends upon the nature of the merging flows at the landings of the escape stairs with occupants from other enclosures and on the flow capacity of the stairs

In the case of a multi-stored building where two floors are evacuated simultaneously and the flow from the upper floor merges with the flow from the floor below, the method described in SFPE Handbook estimates that the flow rate from each floor would be half the maximum flow rate from each storey exit. In some crowded situations, the flow of occupants from in a stairwell from the upper floor may dominate, so that to some extend occupants from the lower floor cannot evacuate until those from the upper floor have gone.

Travel time:
Travel time depends on three components:

- Walking time: the average travel distance to a safe place for the occupants;
- time to queue;
- flow time through the exits.

To estimate the three components, three elements have to be considered:

a) Walking speed
The movement time is obtained by summing the horizontal and the vertical movement time.

Horizontal travel speed: International literature quotes unimpeded walking speed in occupants without physical disabilities as going from 1.2 m/s to 1.25 m/s. Such walking speed may be referred to in case population density is less than 0.54 persons/m^2. In case population density value gets higher, occupants walking speed is impeded: walking speed decreases proportionally to density increase. When population density exceeds 3.8 persons/m^2 speed is considered zero, according to the following equation:

$$S=K-aKD$$

with:
S = speed along the line of travel
D= density (persons/m^2)
K=velocity factor
a=constant 0.266 m^2/pers

Egress Component		K (m/s)
Corridor, aisle, ramp, doorway		1.40
Stair Riser mm	Stair Tread mm	
S1 - 191	254	1.00
S2 - 178	279	1.08
S3 - 165	305	1.16
S4 - 165	330	1.23

Table 9: Velocity factor[7]

Other than using the equation, movement speed as a function of density may be taken from Figure 6.

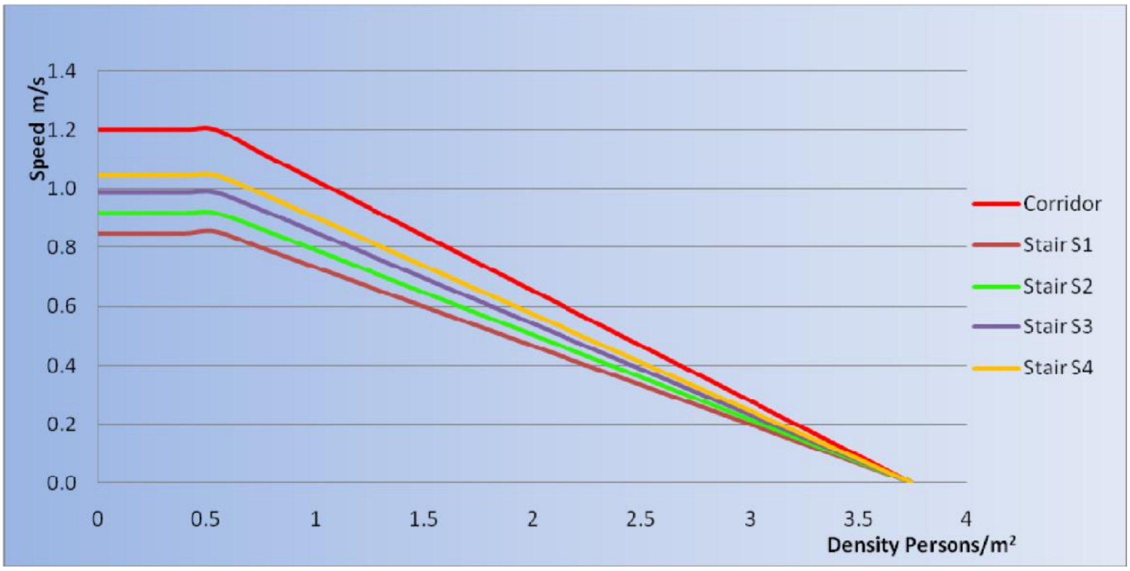


Figure 6 Movement speed as a function of density

[7] PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition"

Vertical travel speed: International literature reports a maximum walking speed variation for not disabled people from 1.1 m/s to 0.85 m/s. This estimation refers to a density of people less than 0.54 persons/m[8]. In the case where the density is higher, occupants are impeded and walking speed decreases proportionally to density increase. When density exceeds 3.8 persons/m^2 walking speed is zero, according to the following equation:

$$S=K-aKD$$

The meaning of each term is the same as that in the previous equation. Factor K refers to table 3.

Many studies present travel data for horizontal and vertical travel speed, in different situations (people with or without disabilities, in crowded or not premises, with different age and gender). A good source for these data is Chapter 64: "Engineering data", from the SFPE Handbook of Fire Protection Engineering, 5th Edition, NFPA Inc., Quincy, Massachusetts, 2015.

b) Specific flow

Specific flow is found by multiplying velocity and density. It states the number of people walking past a point per metre of effective width (door or passageway) per second. Specific flow is similar to the mass flow in a hydraulic system.

$$F_S=SD$$

Substituting S with the previous equation:

$$F_S=SD = (K-aKD)D = (1-aD)KD$$

with:
F_S= Specific flow (persons/ms),
S = speed along the line of travel (m/s),
D= density (persons/m^2),
K=velocity factor,
a=constant 0.266 m^2/pers.

Even specific flow is a function of density, it varies according to the square of density and not proportionally to it as velocity does. The following is a diagram, which describes the specific flow progress, referring to vertical and horizontal travels. The progress of the diagram is that of a parabolic curve which has concavity pointing to the bottom. In the first part, the parabolic curve increases because of the increase of density. When density is 1.9 persons/m^2 (at the top of the curve), the specific flow rate is maximum. In the second part, the parabolic curve decreases: specific flow rate is zero and density 3.8 persons/m^2.

[8] Proulx G., "Evacuation times and movement times in apartment buildings", Fire Safety Journal, 24, 1995

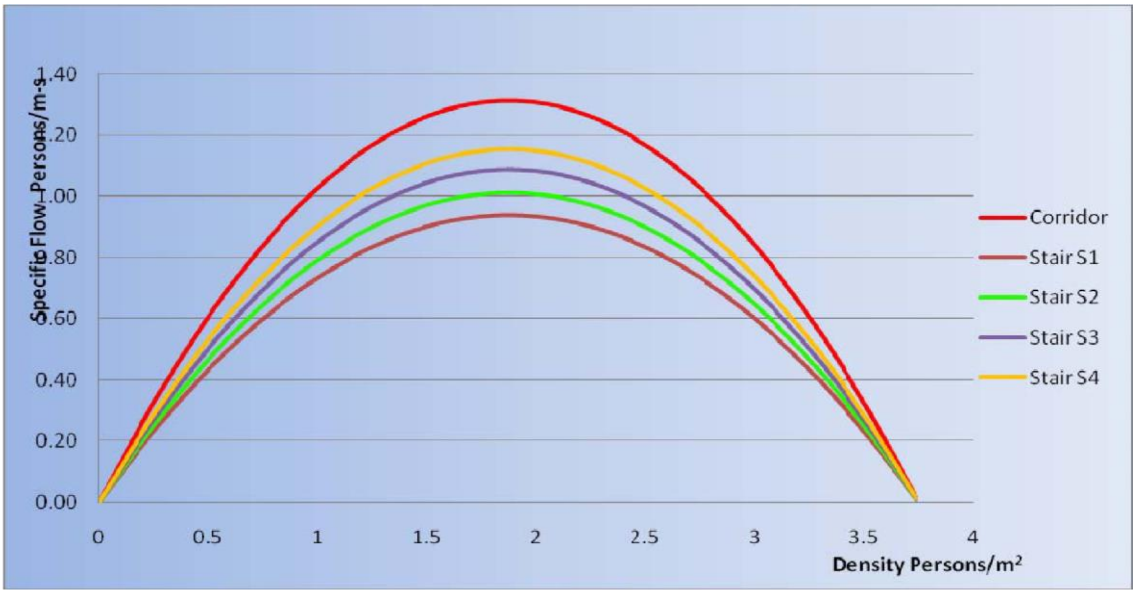


Figure 7: Specific flow as a function of density

It's important to point out the maximum flow capacity for each egress component (corridors, stairs) to give some remarks on flows fusion and transition in egress components. Table 10 shows maximum specific flow rates.

Egress component		F_s pers/sm of effective width
Corridor, aisle, ramp, doorway		1.32
Stair Riser mm	**Stair Tread mm**	
191	254	0.94
178	279	1.01
165	305	1.09
165	330	1.16

Table 10: Maximum specific flows[9]

Where egress components have boundary layers, occupants flow keeping a distance from walls or other obstacles. Doing this, they may have room to move laterally in case of necessity. The result width is given taking away from the all width a variable value given by experimental estimations. Some of the values are reported in table 11.

[9] Source: PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition"

Component	Boundary layer mm
Theater chairs, stadium benches	0
Railings, handrails	90
Obstacles	100
Stairways, door, archways	150
Corridors and ramp walls	200
Wide concourses, passageways	460

Table 11: Boundary layer width[10]

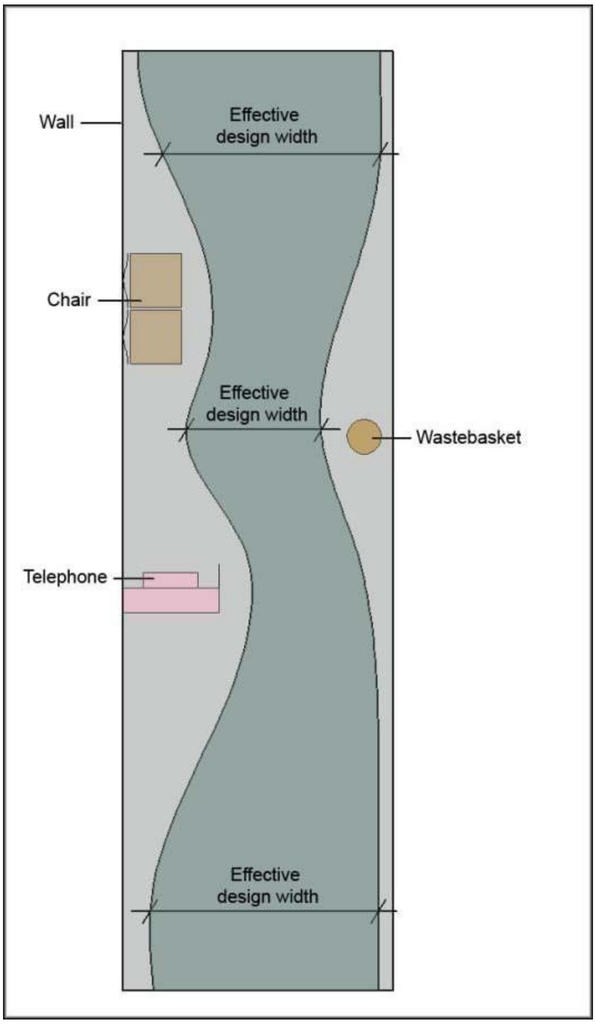


Figure 8: Public corridor effective width[11]

[10]Source: Table 59.1 from Chapter 59: "Employing the Hydraulic Model in Assessing Emergency", The SFPE Handbook of Fire Protection Engineering, 5th Edition, NFPA Inc., Quincy, Massachusetts, 2015

[11] Source: Adapted from fig. 59.6, Chapter 59: "Employing the Hydraulic Model in Assessing Emergency", The SFPE Handbook of Fire Protection Engineering, 5th Edition, NFPA Inc., Quincy, Massachusetts, 2015

c) Flow capacity

It is the number of occupants walking through an egress per second. It may be given multiplying the specific flow with the effective width:

$$F_C = F_S L_e$$

Substituting F_s with the previous formula:

$$F_C = F_S L_e = (1 - aD)KDL_e$$

with:
F_c = flow capacity (persons/s),
F_S= Specific flow (persons/ms)

Follow two particular situations:

Merging egress flow

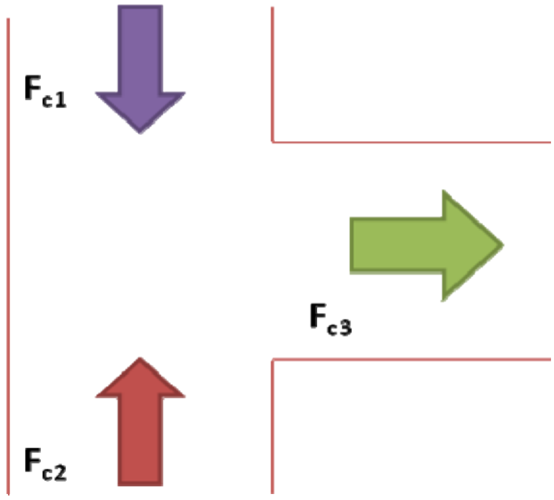


Figure 9: Merging egress flow

The combined flow rate of people entering an intersection equals the flow rate of people from intersection:

$$F_{c1} + F_{c2} = F_{c3}$$
$$F_{s1}L_{e1} + F_{s2}L_{e2} = F_{s3}L_{e3}$$
$$F_{s3} = (F_{s1}L_{e1} + F_{s2}L_{e2}) / L_{e3}$$

If the combined flow rate of egress, components leading to intersections are greater than the specific flow rate for the egress component (see the maximum specific flow rate in table 7 leading from the intersection, a queue is expected to form. If a queue forms, the analysis can continue, considering that the flow rate in component 3 is equal to the maximum capacity of the component.

Transition in egress component

Figure 10: Transitions in egress component

When the width of the egress component changes, then the specific flow is also expected to change. The new specific flow is determined by the following relationship:

$$F_{c1} = F_{c2}F_{s1}L_{e1} = F_{s2}L_{e2}$$
$$F_{s2} = (F_{s1}L_{e1}) / L_{e2}$$

Again, if the incoming specific flow rate leading to the transition point is greater than the capacity of the flow rate for the egress component leading from the transition (see the maximum specific flow rate in table 10), a queue is expected to form at the transition. Specific flow rate after transition is equal to the maximum flow rate which is likely to be actually found.

Impact of smoke on movement:
The emergency movement speeds reported was derived from experiments and observations conducted in smoke-free environments. The remarks in the previous paragraph do not take into consideration the effects of dense smoke. Physiological effects of exposure to smoke have already been discussed previously. Behaviour effects given by seeing the smoke have to be discussed. In a smoke-logged corridor, people tend to turn back rather than continue through the smoke-logged area. In other situations, when people see fires behind them, they tend to move through the smoke.

The presence of smoke will impact movement in two ways:
- It can decrease the probability that occupants will move into an area or continue their evacuation[12]
- It can reduce their walking speed: both the density and optic-irritating properties of the smoke can impact movement speed.

As a supplement on smoke effects, see table 12.

[12] PD 7974-6:2019 "Human factors: Life safety strategies –Occupant evacuation, behaviour and condition", reports that approx. 30% of occupants will not use an escape route if the visibility in that route is less than three meters

Smoke density and irritancy	Approximate visibility	Reported effects
D·m⁻¹(extinction coefficient)	**Diffuse illumination**	
None 0.5 (1.15) non irritant 0.2 (0.5) irritant 0.33 (0.76) mixed	Unaffected 2 m Reduced 3 m	Walking speed 1.2 m/s Walking speed 0.3 m/s Walking speed 0.3 m/s 30% people turn back rather than enter
Suggested tenability limits for buildings with: Small enclosures and travel distances; Large enclosures and travel distances;		$D \cdot m^{-1}=0.2$ (visibility 5m) $D \cdot m^{-1}=0.08$ (visibility 10m)

Table 12: Smoke effects[13]

Annex 5 Main characteristics of evacuation models

Evacuation modelling review

During the last 35 years, several researchers have written many reports concerning evacuation dynamics. Since from 1969 we have surveys describing:

- The movement of people – including disabled people,
- models for evacuation simulations,
- models, which predict the effects of various fire products (heat, toxic and narcotic gases, etc.).

There have been several identifiable generations of evacuation models (which are all still in use):

- 1st generation models involve manual calculations applying mainly prescriptive assumptions;
- 2nd generation models employ computer based flow/hydraulic calculations;
- 3rd generation models use more sophisticated computers than simple flow/hydraulic calculations;
- 4th generations models are the actual state of art and consider several factors (which are discussed below).

Actually the main factors influencing the evacuation performance, and the main factors involved in evacuation modelling, are:

- The spatial configuration of the building (number of exits, exit width, travel distances, etc.),
- the procedures (training, knowledge, signage, etc.),
- the environment (smoke, toxic gases, debris, etc.),
- the human behaviour (response time, travel speeds, route finding, etc.).

All these factors interact and contribute to evacuation performance in a so complex manner that the latest models have to employ numerical and computational processes involving the use of computers to simulate the evacuation process.

The attempts to simulate evacuation with computer modelling fall in two different categories:

- The "movement and behaviour" models;

[13]Source: PD 7974-6:2019 "Human factors: Life safety strategies – Occupant evacuation, behaviour and condition"

- the "ball bearing" models.

The first model takes in account both the physical characteristics of buildings (spatial configuration), and the characteristics and responses of the individual to the external stimuli produced by fire (reaction times, individual behaviour, etc.).

The second model considers people as "objects" which automatically respond to the external stimuli, treating the population within a building as a mass and not as an "individual".

Within these categories, we have further ways to represent:
- The buildings enclosures,
- the population and their behaviour,
- the simulation type.

The enclosures can be represented as "fine" or "coarse" network. In each method, space is divided in sub-regions (or nodes); the size of these regions is the distinguishing parameter.

The coarse node method considers the space divided into "segments" representing a whole room or passageway. The occupants movement is evaluated from segment to segment (e.g.: from room to room), without a precise definition of the real position; so, the representation is less detailed.

The fine node method divides the entire floor space in a collection of nodes (often several hundreds) with fixed size and shape (e.g. 0.5 x 0.5 squares). The occupants' movement is evaluated from node to node; so the representation is more accurate regarding both the enclosures geometry (including obstacles) and the population, which can be treated as individual.

The population, instead, can be represented in an "individual" perspective or in a "global" perspective.

The individual perspective allows several attributes to be assigned to population, which can be used to define the movement and decision making process (if this feature is available). Therefore is possible to represent several population and to trace even a single egress history.

The global perspective does not recognise the individual attributes, defining population as a homogenous whole without differences. Therefore, it is possible to establish only average results, representing evacuation details based on the occupants who escape.

Finally, the simulation itself can be approached in three different ways: optimisation, simulation and risk assessment.

The optimisation models assume that people evacuate efficiently, making the best choice in every situation (evacuation paths are optimal), and that flow features of people and exits are optimal. They tend to consider only large population of occupants.

The simulation models try to reproduce the movement and behaviours observed during real evacuations. For these reasons, the results tend to vary greatly, as does the accuracy, which rely on the sophistication of the model.

The risk assessment model tries to identify the hazards of an evacuation in fire condition, quantifying the associated risks. This model needs many repeated tests with significant statistical variation.

Main characteristics of evacuation models
Evacuation models are hugely available on market. The choice of methods applicable to different design situations is very important.

Models based on movement	Partially behavioural models	Behavioural models
EVACNET4	PEDROUTE/PAXPORT	CRISP
Takahashi's Fluid Model	EXIT89	ASERI
PathFinder	Simulex	BFIRES-2
TIMTEX	GridFlow	buildingEXODUS
WAYOUT	ALLSAFE	EGRESS
Magnetic Model		EXITT
EESCAPE		VEgAS
EgressPro		E-SCAPE
ENTROPY Model		BGRAF
STEPs		EvacSim
		Legion
		Myriad

Table 13: Commercial simulation models

A best evacuation model for each situation does not exist.

The decision to adopt a particular model should agree with computer estimations and limitations.

In general, detailed outputs correspond more complex inputs and longer execution times. Internal parameters have to be distinguished from the external ones. In the model, some internal parameters may be modified (i.e. in fluid dynamics the dimension of the diagram and the time step).

External parameters give input rates. They may be distinguished into three categories:
- Geometrical category (environmental dimensions, ventilation system and access between areas);
- set parameters: knowing about thermic release, velocity of mass reduction, fuel distribution;
- thermophysical category: for example, walls properties (conductibility, specific heat, density, etc.).

The following are some characteristics on simulation models, which are useful to take into consideration for a better choice:

a) Documentation added to the model

1. General information: general information has to report model deficiencies, particularly, model deficiencies about fire hazards. This is a very important point because the correct interpretation of results depends on it.
2. Users' technical and manual documentation: users should be able to know basic scientific references of algorithm. Technical documentation should give users useful information to understand the characteristics of the model:
    - Definition of what kind of fire is, or the functions the model carries out;
    - description of theoretical and physical laws which are at the base of the model;
    - equations which rule the process;
    - identification of the most important hypothesis and their limits on application;
    - description of mathematical techniques and processes, and algorithms used;
    - list of auxiliary programs or data files needed;
    - information about data sources, contents and use.

b) Application on the different buildings

1. Not all models can be applied to every kind of buildings:
    - Model used for the all buildings;
    - model for simulation of residential buildings;
    - model specialized in areas linked to public transport;
    - model to be used in buildings with the maximum height of 20 m;
    - model, which allows simulation with just an evacuation exit.

c) Modelling method

1. Not behavioural: Just movements are considered.
2. Implicit behaviour: Models, which study implicit behaviour, delaying reaction to the alarm (reaction time) or giving occupants characteristics, which influence movements during evacuation.
3. Conditional behaviour (or based on rules): Individual or group of occupants reactions during evacuation, influenced by environmental conditions ("if-then" behaviour: "if" smoke density is higher than "nn", "then" walking speed is reduced).
4. Functional analogy: Models using equations to represent occupants.
5. Artificial intelligence: Models basing on simulation of human intelligence.
6. Probabilistic: Models, which use rules and conditional behaviour basing on probabilistic models. Repeating the same simulation more times, results may be different.

d) Data on fire

It states if user can use information on the fire during simulation.

1. Model can have information on fire from other models.
2. Model allow user to insert data about fire, referred to specific times.
3. Model has a fire simulation model in it.
4. Model cannot have information about fire; it simply simulates the fire (it is similar to a fire training simulates in a building).

e) Data visualization

It can visualize overcrowding and critical points in a building. It is a good way to control probable mistakes in the model.

1. 2-D – Bi-dimensional visualization;
2. 3-D – Tri-dimensional visualization;
3. N – Model with no ability to visualize.

f) Validation

Method, which validates the software and test result rightness, is very important.

1. Validation based on standard.
2. Validation based on data from fire prevention training and evacuation experiments.
3. Validation based on data from literature about evacuation experiments.
4. Validation based on other models.
5. Models with no validation suggested.

European guidelines

Fire

Guideline No 1 F - Internal fire protection control
Guideline No 2 F - Panic & emergency exit devices
Guideline No 3 F - Certification of thermographers
Guideline No 4 F - Introduction to qualitative fire risk assessment
Guideline No 5 F - Guidance signs, emergency lighting and general lighting
Guideline No 6 F - Fire safety in care homes
Guideline No 7 F - Safety distance between waste containers and buildings
Guideline No 8 F - withdrawn
Guideline No 9 F - Fire safety in restaurants
Guideline No 10 F - Smoke alarms in the home
Guideline No 11 F - Recommended numbers of fire protection trained staff
Guideline No 12 F - Fire safety basics for hot work operatives
Guideline No 13 F - Fire protection documentation
Guideline No 14 F - Fire protection in information technology facilities
Guideline No 15 F - Fire safety in guest harbours and marinas
Guideline No 16 F - Fire protection in offices
Guideline No 17 F - Fire safety in farm buildings
Guideline No 18 F - Fire protection on chemical manufacturing sites
Guideline No 19 F - Fire safety engineering concerning evacuation from buildings
Guideline No 20 F - Fire safety in camping sites
Guideline No 21 F - Fire prevention on construction sites
Guideline No 22 F - Wind turbines – Fire protection guideline
Guideline No 23 F - Securing the operational readiness of fire control system
Guideline No 24 F - Fire safe homes
Guideline No 25 F - Emergency plan
Guideline No 26 F - withdrawn
Guideline No 27 F - Fire safety in apartment buildings
Guideline No 28 F - Fire safety in laboratories
Guideline No 29 F - Protection of paintings: transports, exhibition and storage
Guideline No 30 F - Managing fire safety in historic buildings
Guideline No 31 F - Protection against self-ignition end explosions in handling and storage of silage and fodder in farms
Guideline No 32 F - Treatment and storage of waste and combustible secondary raw materials
Guideline No 33 F - Evacuation of people with disabilities
Guideline No 34 F - Fire safety measures with emergency power supply
Guideline No 35 F - Fire safety in warehouses
Guideline No 36 F - Fire prevention in large tents
Guideline No 37 F - Photovoltaic systems: recommendations on loss prevention
Guideline No 38 F - Fire safety recommendations for short-term rental accommodations
Guideline No 37 F - Fire protection in schools
Guideline No 38 F - Fire safety recommendations for short-term rental accommodations
Guideline No 39 F - Fire protection in schools
Guideline No 40 F - Procedure to certify CFPA-E Fire Safety Specialists in Building Design

Natural hazards

Guideline No 1 N - Protection against flood

Guideline No 2 N - Business resilience – An introduction to protecting your business
Guideline No 3 N - Protection of buildings against wind damage
Guideline No 4 N - Lighting protection
Guideline No 5 N - Managing heavy snow loads on roofs
Guideline No 6 N - Forest fires
Guideline No 7 N - Demountable / Mobile flood protection systems

Security
Guideline No 1 S - Arson document
Guideline No 2 S - Protection of empty buildings
Guideline No 3 S - Security systems for empty buildings
Guideline No 4 S - Guidance on keyholder selections and duties
Guideline No 5 S - Security guidelines for museums and showrooms
Guideline No 6 S - Security guidelines emergency exit doors in non-residential premises
Guideline No 7 S - Developing evacuation and salvage plans for works of art and heritage buildings
Guideline No 8 S - Security in schools
Guideline No 9 S - Recommendation for the control of metal theft
Guideline No 10 S - Protection of business intelligence
Guideline No 11 S - Cyber security for small and medium-sized enterprises

Comments and corrective actions:

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