TECHNICAL SPECIFICATION

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Fire safety engineering — Selection of design fire scenarios and design fires —

Part 2: Design fires

Ingénierie de la sécurité incendie — Sélection de scénarios d'incendie et de feux de dimensionnement —

Partie 2: Feu de dimensionnement

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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 procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

A list of all parts in the ISO 16733 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides guidance for the specification of design fires for use in fire safety engineering analysis. A design fire is linked to a specific scenario that is tailored to the fire-safety design objective. There can be several fire safety objectives being addressed, including safety of life (for occupants and rescue personnel), conservation of property, protection of the environment and preservation of heritage. A different set of design fire scenarios and design fires can be required to assess the adequacy of a proposed design for each objective.

The procedure for the selection of the design fire scenarios is described in ISO 16733-1. The design fire can be thought of as an engineering representation of a fire or a “load” that is used to determine the consequences of a given fire scenario. The set of assumed fire characteristics are referred to as “the design fire”. In this document, various formulae are presented to calculate different phenomena. Formulae other than those presented here can also be applicable for a given application.

It is important that the design fire be appropriate to the objectives of the fire-safety engineering analysis. It should challenge the fire safety systems in a specific built environment and result in a final design solution that satisfies performance criteria associated with all the relevant design objectives.

Users of this document should be appropriately qualified and competent in the field of fire safety engineering. It is important that users understand the parameters within which specific methodologies may be used.

ISO 23932-1 provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property, heritage and the environment. ISO 23932-1 provides the process (necessary steps) and essential elements for designing a robust, performance-based fire safety programme.

ISO 23932-1 is supported by a set of ISO fire safety engineering standards available on the methods and data needed for the steps in a fire safety engineering design summarized in ISO 23932-1:2018, Clause 4 and shown in Figure 1. This system of standards provides an awareness of the interrelationships between fire evaluations when using the set of ISO fire safety engineering standards.

Each document includes language in the introductory material of the document to tie it to the steps in the fire safety engineering design process outlined in ISO 23932-1. Selection of design fire scenarios and design fires form part of conformance with ISO 23932-1, and all the requirements of ISO 23932-1 apply to any application of this document.

This document provides a more comprehensive treatment of the content of ISO 16733-1:2015, Annex C.

Fire safety engineering — Selection of design fire scenarios and design fires —

Part 2: Design fires

1 Scope

This document provides guidance for the specification of design fires for use in fire safety engineering analysis of building and structures in the built environment. The design fire is intended to be used in an engineering analysis to determine consequences in fire safety engineering (FSE) analyses.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
combustion efficiency
ratio of the amount of heat release in incomplete combustion to the theoretical heat of complete combustion

Note 1 to entry: Combustion efficiency can be calculated only for cases where complete combustion can be defined.

Note 2 to entry: Combustion efficiency is dimensionless and is usually expressed as a percentage.

3.2
design fire
quantitative description of assumed fire characteristics within a *design fire scenario* (3.3)

Note 1 to entry: Typically, an idealized description of the variation with time of important fire variables, such as heat release rate and toxic species yields, along with other important input data for modelling such as the fire load density.

3.3
design fire scenario
specific *fire scenario* (3.9) on which a deterministic fire safety engineering analysis is conducted

Note 1 to entry: As the number of possible fire scenarios can be very large, it is necessary to select the most important scenarios (the design fire scenarios) for analysis. The selection of design fire scenarios is tailored to the fire-safety design objectives, and accounts for the likelihood and consequences of potential scenarios.

3.4
effective heat of combustion
heat released from a burning test specimen in a given time interval divided by the mass lost from the test specimen in the same time period

Note 1 to entry: This is the same as the net heat of combustion if all the test specimen is converted to volatile combustion products and if all the combustion products are fully oxidized.

Note 2 to entry: The typical units are kilojoules per gram ($kJ \cdot g^{-1}$).

3.5
extinction coefficient
natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length

Note 1 to entry: Typical units are reciprocal metres (m^{-1}).

3.6
fire growth
stage of fire development during which the *heat release rate* (3.15) and the temperature of the fire are increasing

3.7
fire load
quantity of heat which can be released by the complete combustion of all the combustible materials in a volume, including the facings of all bounding surfaces

Note 1 to entry: Fire load may be based on *effective heat of combustion* (3.4), gross *heat of combustion* (3.14), or net heat of combustion as required by the specifier.

Note 2 to entry: The word “load” can be used to denote force or power or energy. In this context, it is being used to denote energy.

Note 3 to entry: The typical units are kilojoules (kJ) or megajoules (MJ).

3.8
fire load density
fire load (3.7) per unit area

Note 1 to entry: The typical units are kilojoules per square metre ($kJ \cdot m^{-2}$).

3.9
fire scenario
qualitative description of the course of a fire with time, identifying key events that characterize the fire and differentiate it from other possible fires

Note 1 to entry: The fire scenario description typically includes the ignition and fire growth processes, the *fully developed fire* (3.13) stage, the fire decay stage, and the environment and systems that will impact on the course of the fire. Unlike deterministic fire analysis, where fire scenarios are individually selected and used as *design fire scenarios* (3.3), in fire risk assessment, fire scenarios are used as *representative fire scenarios* (3.10) within *fire scenario clusters*.

[SOURCE: ISO 13943:2008, 4.129, modified]

3.10
representative fire scenario
specific *fire scenario* (3.9) selected from a *fire scenario cluster* (3.11) such that the consequence of the representative fire scenario can be used as a reasonable estimate of the average consequence of scenarios in the fire scenario cluster

3.11
fire scenario cluster
subset of *fire scenarios* (3.9), usually defined as part of a complete partitioning of the universe of possible fire scenarios

Note 1 to entry: The subset is usually defined so that the calculation of fire risk as the sum over all fire scenario clusters of fire scenario cluster frequency multiplied by *representative fire scenario* (3.10) consequence does not impose an undue calculation burden.

3.12
flashover
transition to a state of total surface involvement in a fire of combustible materials within an enclosure

3.13
fully developed fire
state of total involvement of combustible materials in a fire

3.14
heat of combustion
thermal energy produced by combustion of unit mass of a given substance

Note 1 to entry: The typical units are kilojoules per gram ($kJ \cdot g^{-1}$).

3.15
heat release rate
rate of thermal energy production generated by combustion

Note 1 to entry: The typical units are watts (W).

3.16
target
a person, object or environment intended to be protected from the effects of fire and its effluents (smoke, corrosive gas, etc.) and/or fire suppression effluents

4 Symbols

A_t	total area of enclosure (walls, ceiling and floor, including openings), m^2
A_T	total area of enclosure (walls, ceiling and floor, excluding openings), m^2
A_f	horizontal burning area of the fuel, m^2
A_{fl}	floor area, m^2
A_o	area of opening, m^2
b	thermal inertia of linings, $J/(m^2 s^{1/2} K)$
c	distance of target from the centre of the flame, m
c_p	specific heat, J/(kg K)
D	fire diameter, m

e	represents the mathematical constant - Euler's number
f	flapping length
f_a	flapping angle
$f_s(s)$	probability distribution for RSET
$f_s(x)$	probability distribution for ASET
$q_{f,d}$	fire load energy density, MJ/m^2
F_s	non-dimensionless form of fire
h_g	heat of gasification of the fuel, kJ/kg
h_T	average effective heat transfer coefficient, kW/(m^2 K)
h'	heat flux, W/m^2
h'_{net}	net heat flux, W/m^2
H	vertical distance between the fire source and the ceiling, m
H_o	height of an opening, m
L	length of the compartment, m
L_d	length of the design area involved in fire, m
L_f	vertical flame height, m
L_H	horizontal flame length, m
$\dot{m}_f$	rate of mass loss of fuel, kg/s
$\dot{m}_{F,u}$	mass loss rate of fuel under well ventilated free burn conditions, kg/s
m_g	mass of fuel burned during the growth phase, kg
$\dot{m}_{out}$	rate of entry of air outflow from the enclosure, kg/s
$\dot{m}_p$	mass flow of gases entrained into the fire plume, kg/s
$\dot{m}_s$	mass loss rate for smouldering combustion, g/min
m_{tot}	total mass of fuel burned, kg
$\dot{m}''$	mass loss rate per unit area, kg/(s m^2)
O	opening factor, m$^{1/2}$
$\dot{q}_{ext}$	total external heat flux from the smoke and heated enclosure boundary surfaces, kW
$q_{f,d}$	fire load density per unit floor area, MJ/m^2
$\dot{q}''$	heat flux, kW/m^2
$\dot{Q}$	heat release rate, kW
$\dot{Q}_c$	convective part of the heat release rate, W/m^2

$\dot{Q}_{fo}$ minimum heat release rate to cause flashover, kW

$\dot{Q}_{H}$ non-dimensional heat release rate

$\dot{Q}_{max}$ maximum heat release rate, kW

$\dot{Q}_{v}$ ventilation-controlled heat release rate, kW

$\dot{Q}''$ heat release rate per unit area, kW/m^2

r stoichiometric air requirement for complete combustion of fuel, expressed as the mass ratio of air to fuel

r_d horizontal distance between the vertical axis of the fire and the point along the ceiling where the thermal flux is calculated, m

r_x radial distance away from the fire, m

s fire spread rate, m/s

t time, s

t_b burning time, s

t_g time required to reach the reference heat release rate $\dot{Q}_o$, s

t_{gw} time at which the heat release rate reaches a maximum value, s

t_{lim} limiting time, h

t_{tot} total burning time, s

T_a room temperature, °C

T_f reduced near-field temperature due to flapping, °C

T_{nf} near-field temperature, °C

W width of the compartment, m

$\S_r$ radiative fraction of the total energy

y dimensionless constant

Y_{O2} mass fraction of oxygen in the plume flow, kg/kg

$Y_{o,l}$ mass fraction of oxygen in the gases feeding the flame, kg/kg

$Y_{o,\infty}$ mass fraction of oxygen under ambient free-burning conditions, kg/kg

z height along the flame axis, m

z_o virtual origin of the axis, m

z' vertical position of the virtual heat source, m

α fire growth coefficient, kW/s^2

α_c convective heat transfer coefficient

Γ dimensionless ventilation parameter

ΔH_c chemical heat of combustion, kJ/kg

ΔH_{eff} effective heat of combustion, kJ/kg

ΔH_{O2} heat of combustion based on oxygen consumption, MJ/kg (~13,1 for hydrocarbons)

ε_f emissivity of the fire

ε_m surface emissivity of the member

θ_m surface temperature of the member, °C [see Formula (21)]

Θ_g parametric fire gas temperature, °C

ρ_b density of boundary, kg/m^3

σ Stefan Boltzmann constant

λ thermal conductivity, W/(m K)

τ_d duration of the decay burning stage, s

τ_{gw} duration of the growing fire stage, s

τ_s duration of the steady burning stage, s

Φ configuration factor

χ combustion efficiency

5 The role of design fires in fire safety design

Design fire specifications play a critical role in fire safety engineering. It is important that the procedures described in ISO 23932-1 be followed. This means that the fire safety objectives and performance criteria are stated and the relevant design scenarios are identified using ISO 16733-1 for fire scenarios and ISO/TS 29761 for behavioural scenarios.

Figure 1, taken from ISO 23932-1, illustrates the fire safety design process. The specification of design fires follows the scenario selection step and provides input data for the selected engineering methods. Following identification of the design fire scenarios in accordance with ISO 16733-1, the assumed characteristics of the fire on which the scenario quantification will be based shall be described. The assumed fire characteristics and the associated fire development over time are generally referred to as the "design fire".

This document is applicable to design fires that are quantifiable in engineering terms and therefore intended to form part of a deterministic or combined deterministic/probabilistic analysis. A deterministic approach calculating the consequence of individual fire scenarios may also form part of an overriding probabilistic analysis. For example, Monte Carlo simulation can be used to quantify uncertainty using statistical techniques in both inputs and outputs.

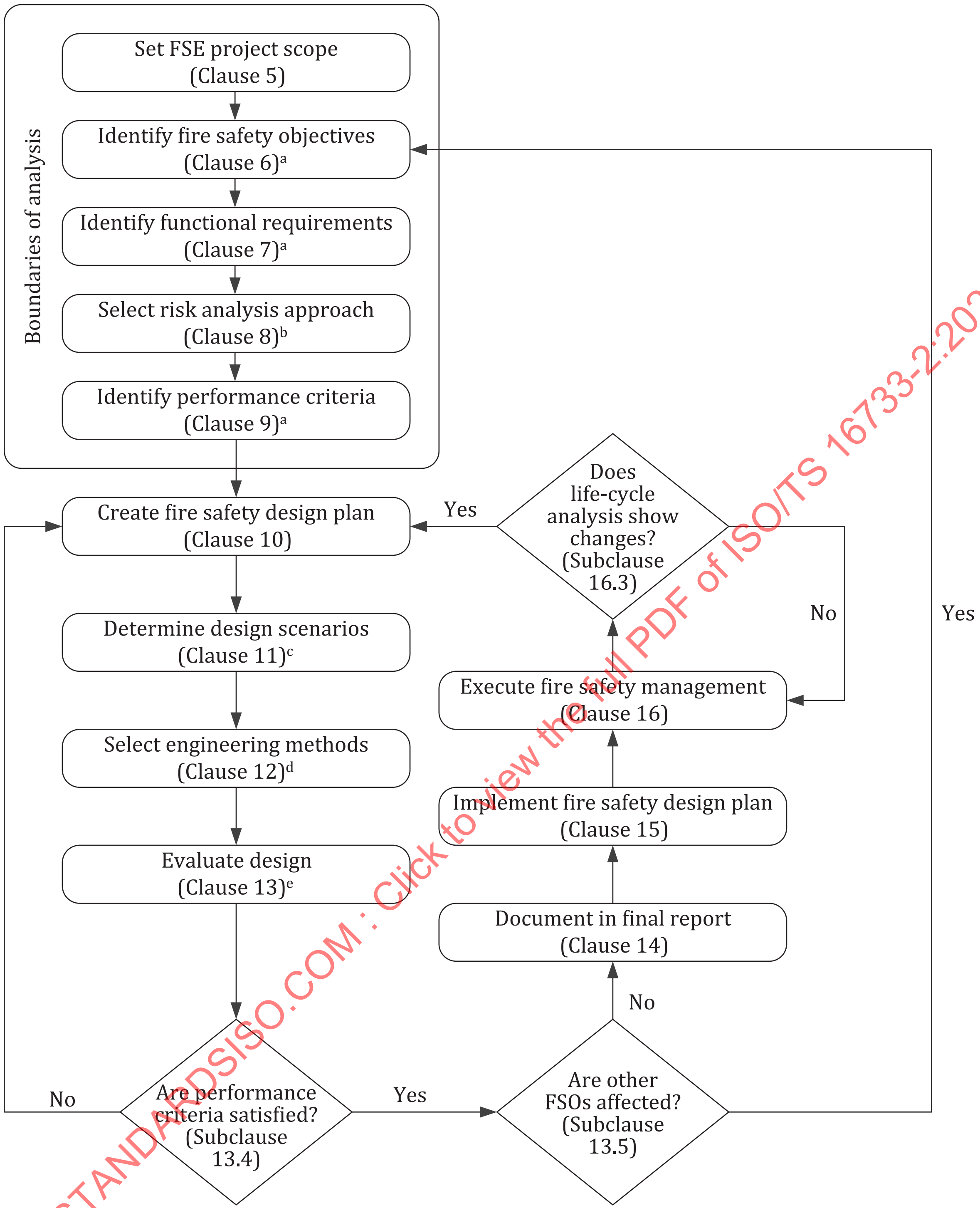
This document is also intended to accommodate a range of different analysis methods, including use of computational fluid dynamics models (CFD), zone models, or simple hand calculations. Each approach can require the use of different parts of this document. Some calculations may be handled within the analysis model, such as determining the ventilation limit or determining effect of suppression systems, while simpler analysis methods can require these elements to be estimated separately. Where computer models are used for the analysis, it is important for the engineer to understand the model limitations and which fire or other phenomena are included and not included. The model or tool selected for use should be appropriate for the overall analysis as described in ISO 23932-1:2018 Clause 11.

The nature of the fire scenario can require the application of selected clauses of this document rather than all parts. For example, where the fire scenario predominantly concerns:

— a growing or developing fire, refer to Clause 8.

— a smouldering fire, refer to Clause 9.

— a fully developed fire affecting structure, refer to Clause 10.



Key

a See also ISO/TR 16576 (Examples).

b See also ISO 16732-1, ISO 16733-1, ISO/TS 29761.

c See also ISO 16732-1, ISO 16733-1, ISO/TS 29761.

d See also ISO/TS 13447, ISO 16730-1, ISO/TR 16730-2, ISO/TR 16730-3, ISO/TR 16730-4, ISO/TR 16730-5 (Examples), ISO 16734, ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-6.

e See also ISO/TR 16738, ISO 16733-1.

Figure 1 — Flow chart illustrating the fire safety design process and selection of design fire scenarios (Source: ISO 23932-1)

Clause 11 covers several specific correlations for external fire exposures.

Clause 12 discusses the use of fire tests for developing design fires when engineering calculation methods are not available or not applicable.

Where analysis involving probabilistic aspects of design fires are envisaged, readers should also refer to Clause 13 in addition to the relevant subclauses of Clauses 8-12.

The design fire can include descriptions of the heat release rate, gas temperature or heat fluxes as well as the yields of smoke and other combustion products. The most important parameter of the design fire is the heat release rate and different approaches are available to develop a design fire curve for the time-varying heat release rate from a fire. In general, the main approaches are:

1) To calculate the fire growth and heat release from first principles based on an understanding of the product materials and geometry, chemistry and underlying combustion processes.

   This is generally difficult and can currently be considered insufficiently reliable for general use in fire safety engineering. It is not discussed further in this document.

2) To construct composite heat release rate curves from the individual components.

   This is more applicable when information is known regarding the specific contents and their arrangement within the built environment. This requires consideration and estimation of fire spread from the ignition source to other nearby items and the relevant timeline for this to occur.

3) To assume a generalized heat release rate curve (e.g. t^2 fire).

   This may include a representative fire growth rate for different well-defined occupancies. This could be based on experimental data. It does not require fire spread from individual items to be assessed and is therefore very simple to apply. This approach may be prescribed in some codes of practice (see Annex A).

Initially, the engineer should determine the design heat release rate curve, without intervention, as would apply if the fire were allowed to develop in well-ventilated, open-air conditions. Interventions result in a potential change in the course of the fire. They could include:

— manual fire-fighting actions by occupants or by trained fire-fighters;

— automatic or manually operated fire suppression systems;

— restricted ventilation or changes in ventilation during the course of the fire (e.g. glass breaking);

— burning enhancement due to thermal feedback from the hot gases and enclosure surfaces to the fuel surface.

The selected approach will depend on what is known about the fire scenario and the items involved. The method of analysis may also determine the approach being dependent of what input information is available.

A complete description of the design fire from ignition to decay is estimated using the specified initial conditions and a series of simple calculations to estimate parameters such as the sprinkler activation time, transition to flashover and duration of any fully developed burning.

Alternatively, the design fire can be a combination of quantified initial conditions and subsequent fire development determined iteratively or by calculation using more detailed models that account for phenomena such as transient effects of changing ventilation on smoke production or thermal feedback effects from a hot layer to the fuel surface.

As with the design fire scenario, it is important that the design fire be appropriate to the relevant fire-safety objectives. For example, if safety of life is an objective, and the built environment includes a smoke control system, a design fire should be selected that challenges the smoke control system. If the severity of the design fire is underestimated, then the application of engineering methods to predict the effects of the fire can produce results that do not accurately reflect the true impact of fires and can underestimate the hazard. Conversely, if the severity is overestimated, unnecessary expense can result. It is important to appreciate that in real life, due to uncertainties associated with the fuel, ventilation and other factors, the actual severity of the fire varies according to statistical distribution.

6 Considerations based on methods of analysis

It is common for fire models to include some of the dynamic changes and stage transitions expected over the duration of the fire. For example, when a fire model constrains the heat release rate within a compartment to match the available oxygen supply. Other dynamic effects may not be included such as fracture and fallout of glazing within the compartment walls. The engineer is required to assess which elements of the design fire are required for a specific analysis allowing for those predicted by the fire model as well as those required as input to the model.

Whereas most advanced models require the heat release rate of the fire as input to a calculation of the enclosure temperature or other fire properties, there is a class of models that is simpler in nature and requires less sophisticated input data. For example, the parametric fire curves for post-flashover fires discussed in subclause 10.3 do not require estimates of the heat release rate of the fire as input. Instead, the gas temperature is predicted directly, employing simpler information, such as the geometry of the enclosure and its ventilation openings, the thermal properties of room lining materials and the fuel load.

For a given design fire scenario, the parameters determined in Clause 8 can be employed to predict the temperature/heat flux evolution versus time and the associated effluents using various calculation methods ranging in their complexity from simple to advanced.

7 Elements of a design fire

7.1 General

Fire can grow from ignition through to a fully developed stage and finally decay and eventual extinction. The design fire is described by the values of variables, such as the heat release rate and yield of combustion species, over the life of the fire.

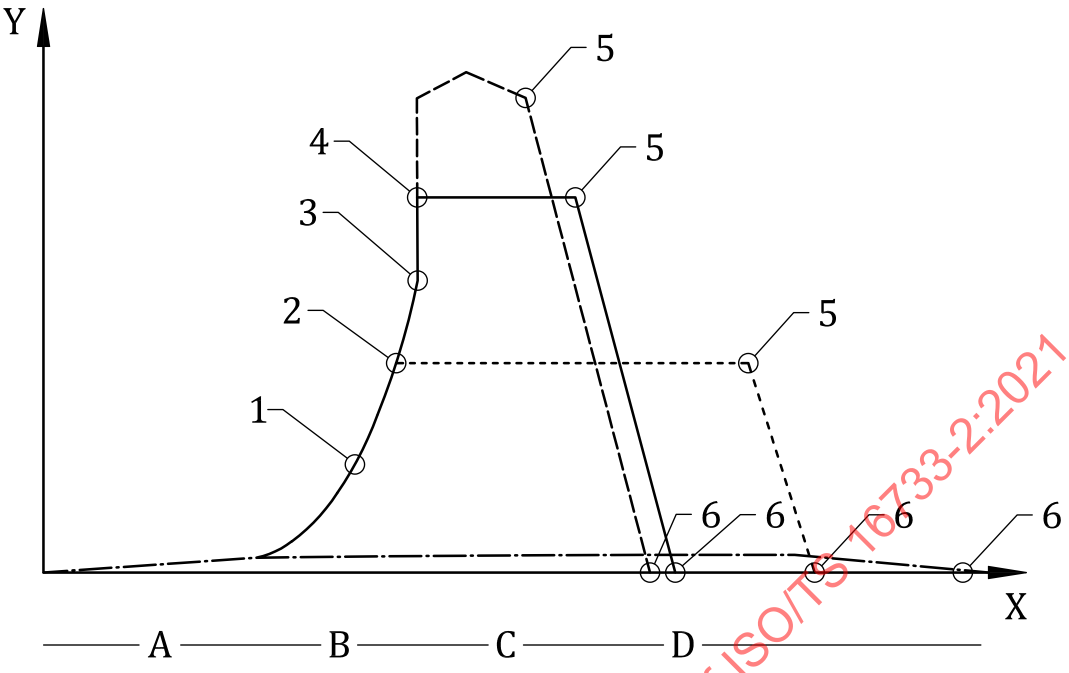
A full specification of a design fire (see Figure 2) can include the following phases:

— incipient stage (A): characterized by a variety of sources, which can be smouldering, flaming or radiant.

— growth stage (B): covering the fire propagation period up to flashover or full fuel involvement.

— fully developed stage (C): characterized by a substantially steady burning rate determined from either the ventilation supply or the fuel surface area. During this stage, the heat output within an enclosure is generally the lesser of the ventilation-controlled heat output and the fuel-surface-area-controlled (under free burn conditions) heat output. If the fuel bed-controlled rate exceeds the ventilation-controlled rate, then the difference can potentially contribute to burning external to the enclosure.

— decay stage (D): covering the period of declining fire intensity until extinction.



Key

- · - · - incipient - smouldering
- - - - - sprinkler-controlled
——— ventilation-controlled
— — — fuel-controlled

X	time
Y	heat output
1	growth
2	sprinkler activation
3	flashover
4	ventilation limit
5	decay
6	extinction

Figure 2 — Example of design fire

Design fire characteristics can be subsequently modified based upon the stepwise results of the analysis. For example, in case of a fire in a small/medium sized compartment, if the single-item fire grows sufficiently intense that flashover in an enclosure is likely, it is necessary to modify the design fire to reflect the characteristics of a ventilation-controlled or fuel-bed-controlled, fully-developed fire as well as involvement of additional burning items, if present. Similarly, events such as sprinkler activation and window breakage can influence the subsequent description of the design fire.

Consequently, a design fire can be a description of the fire over the full duration of the fire. This description may include the following:

— parameters provided by the design-fire scenario (size of the room, location of the fire, combustible material under consideration, etc.);

— parameters required to evaluate the fire development (heat release rate and other parameters, depending on the assessment model to be used);

— events that result in a change in any of the above parameters.

Design fires are usually characterized in terms of one or more of the following variables with respect to time (as needed by the fire safety objective(s) and consequently by the analysis):

— heat release rate;

— combustion product species generation rate;

— smoke production rate;

— flame height/volume;

— burning area;

— temperature/heat flux.

The appropriateness of the selection of the design fire depends on the objectives of the engineering assessment. For example, a design fire for smoke control purposes can have different characteristics and definition metrics compared to a design fire for assessing structural fire resistance.

7.2 Incipient stage

A smouldering fire typically produces very little heat but can, over a sufficiently long period, fill an enclosure with unburned combustible gases, toxic products of combustion such as carbon monoxide and soot. Entrainment into these smouldering fires is low, resulting in high rates of release of smoke and toxic species per unit of mass burned[1].

The following factors affect the likelihood of onset of smouldering combustion:

— nature of the fuel and the propensity to form char;

— local air currents;

— strength and characteristics of the ignition source.

Smouldering fires can readily transform into flaming fires, particularly when air flow across the surface is increased. The principal hazard associated with smouldering fires is the production of carbon monoxide as a result of incomplete combustion. The development of untenable conditions due to poor visibility is also a significant hazard that it is important to consider in the analysis, particularly in residential occupancies.

7.3 Growth stage

The factors determining the characteristic rate of fire growth for flaming fires include the following:

— nature of combustibles and burning properties (e.g. heat of combustion, heat of gasification, etc.);

— geometric arrangement of the fuel;

— size and geometry of the enclosure (fire growth can vary for the same combustibles burning inside an enclosure compared to burning in the open; see also 7.6.5);

— strength and characteristics of the ignition source;

— ignitability of the fuel;

— ventilation;

— external heat flux;

— exposed surface area (and surface area to mass ratio).

The initial rate of fire growth is subsequently modified by events that occur during the design fire scenario. These events can modify the heat release rate and smoke generation rate of the fire either positively or negatively. Typical events and their effects on the fire are the following:

— flashover	transition to a state of full involvement in the fire compartment;
— low hot layer interface	acceleration;
— sprinkler activation	steady or declining;
— manual fire suppression	steady or declining;
— fuel exhaustion	decay;
— changes in ventilation	transition between fuel control and ventilation control;
— flaming debris	subsequent ignition(s) of other items.

It is important that a determination of the rate of initial fire growth includes these aspects. Fire models are available that can predict rate of fire growth on simple fuel geometries under defined conditions. Experimental data are also available [2,3] to assist in the determination of rate of fire growth on typical fuel packages.

Further guidance on determining the fire growth rate and heat release rate for single or multiple fuels is given in 8.3, and for power law design fire curves in 8.3.4.

7.4 Flashover

Flashover is the rapid transition from a localized fire to the involvement of all exposed surfaces of combustible materials within an enclosure. It occurs somewhat commonly in small and medium size enclosures. In large volume compartments flashover can not occur. In these cases, the fire could either remain localized or progressively spread to adjacent fuel (travelling fires). Depending on the purpose of the assessment, such non-uniform fires can also need to be selected as a complementary design fire (see Clause 10 on structural design fires, for example).

The effect of flashover on the design fire is to modify the heat release rate and other characteristics to those appropriate to a fully developed fire. This can include changes in the yields of species generated by the fire. For example, the rate of generation of carbon monoxide and soot increases as the combustion environment becomes ventilation limited.

Further guidance on determining the time for the occurrence of flashover is given in 8.4.

Species yields are discussed in 9.1.

7.5 Fully developed stage

Typically, following flashover, fires tend to rapidly reach a fully developed stage where the heat release rate is a maximum and is limited either by the fuel area or the available ventilation. For some specific fuel configurations (e.g. cribs) the burning can also be limited by porosity. The maximum heat release rate within a compartment following flashover may be taken as the lesser of the ventilation-controlled, porosity-controlled (if applicable) and fuel-surface-area-controlled heat release rates.

The ventilation-controlled rate of burning in a compartment can be determined from consideration of air/oxygen flowing into the compartment, whereas the burning rate of fuel-bed-controlled fires is dependent upon the nature and surface area of the fuel.

The duration of burning will be mainly dependent on the amount of fuel available and the rate at which it can be pyrolyzed. When flashover does not occur within a compartment and travelling fire develops, the fire can also reach a fully developed stage where the fire has reached its maximum intensity.

Further guidance on determining the maximum heat release rate and the duration of burning is given in 8.5 and 8.7 respectively.

7.6 Events that change a design fire

7.6.1 General

During the period of fire development there are various events that can change the way in which the fire develops in the future. Some of these are mentioned in this subclause. However, this list is not exhaustive.

7.6.2 Suppression systems

Suppression systems, if installed, could be either automatically or manually operated. Suppression systems can operate at any time during the fire but are normally expected to operate during the pre-flashover stage. Depending on the type of suppression system present and other circumstances, the fire can be affected in one of the following ways:

a) fire continues to grow at a reduced rate;

b) fire growth stops and the heat release rate remains constant;

c) fire growth stops and the heat release rate decreases.

The performance of a suppression system can be affected by several factors, including the height of installation relative to the fire source location, particularly for sprinkler systems. There can be shielding of the combustibles from the suppression agent. The volume of the compartment and location and size of ventilation openings including leakage paths can also be important, particularly for gaseous fire suppression systems. Manual suppression by occupants can also occur and can affect the fire development depending on training, agent availability and timeliness of application.

The heat-release rate following activation of a sprinkler system can be taken as remaining constant, unless it can be demonstrated that the sprinkler system has been designed to suppress the fire within a specified period. In the latter case, the heat-release rate can be assumed to decrease in a linear manner over the specified period following activation of the sprinkler.

Similarly, activation of a total flooding gaseous fire suppression system designed in accordance with the relevant ISO or national standard can be assumed to suppress the fire soon after the design concentration of extinguishing agent has been reached.

Further guidance on determining the effect of suppression systems on the design fire curve is given in 8.6.1.

7.6.3 Intervention by fire services

The fire services may intervene at any time during the development of the fire, but it is likely that they can control the fire only if it is within the capabilities of the appliances in attendance. The effect of the fire services on the fire is dependent on factors such as the means of notification of the fire, the location and distance of the built environment from fire stations, the resources available to the fire services, site access conditions and adequacy of the water supplies. It is important that the design fire challenges the capability of fire services to carry out rescue and firefighting activities and therefore it may differ from other design fires intended to challenge other fire safety systems. For example, a longer fire growth stage can result in more challenging conditions at the time of fire service arrival compared to a fire that is in decline. It can also be necessary to consider the effect of the fire on fire services personnel to assess their effectiveness in carrying out rescue or fire-fighting activities. Fire services may also use fans to redirect smoke and improve conditions for firefighting.

Unless an appropriate model for fire brigade intervention and effectiveness is used (for example, see References [4] and [5]), special care should be taken when accounting for fire brigade intervention, as the actual effects of their intervening actions are not generally predictable in models.

Further guidance on determining the effect of intervention by fire services on the design fire curve is given in 8.6.2.

7.6.4 Changes in ventilation

Early in the fire development period, smoke management systems may be used to improve the environment during the evacuation period. These systems may either rely on mechanical components such as fans, or on natural ventilation using high level openings. In both cases, a means of providing low level make-up air is required. Design of smoke management systems is a specialized area and there are various design guides available to the engineer[6-8]. The design of these systems is outside the scope of this document.

Changes in fixed ventilation can also occur during the fire that influence the future development of the fire. These changes can be the result of glass breaking and falling out, or when openings form in parts of the wall or roof construction due to burn through or collapse. These provide an additional source of air/oxygen which can either increase the intensity of burning, or else aid in the removal of combustion products from the compartment.

Further guidance on determining the effect of changes in ventilation on the design fire curve is given in 8.6.3.

7.6.5 Enclosure effects

Fire growth rates can be influenced by thermal feedback to the surface of the fuel due to the flames, the hot gases and other surfaces. Care is required interpreting fire test data which are often obtained under well-ventilated open burning conditions and are therefore representative of large, well-ventilated rooms (compared to the size of the fire). In smaller, confined enclosures, radiation feedback to the fuel can accelerate the fire growth and increase the mass loss rate and total heat release rate from the fuel. The size of this effect also depends on the type of fuel (e.g. cellulosic, plastic, hydrocarbon). Furthermore, under some conditions the combustion products can mix with the incoming air flow and lead to a reduction in the oxygen concentration in the gases feeding the flame. This is turn can reduce the mass loss rate.

Further guidance on determining the effect of the enclosure on the pyrolysis of the fuel is given in 8.6.4.

7.6.6 Combustible construction materials

Where enclosures have combustible linings and structural elements exposed to the fire (e.g. timber) they can provide additional fuel that changes the fire dynamics, thus increasing early fire hazard as well as the overall severity of the enclosure fire. These changes can be affected by the location and surface area of the combustible materials or by the failure of any protective linings such as gypsum plasterboard. In the case of cross-laminated timber, new layers of virgin wood can be exposed in the event of debonding of lamella. This can occur if the adhesive used does not maintain strength when its temperature increases, leading to situations where the fire shows regrowth after lamella debonding[9]. Large quantities of combustible materials on the walls and ceiling can also lead to more pronounced external flames from openings in the walls with a higher risk of external fire spread.

Further guidance on assessing the influence of combustible walls and ceilings on the design fire curve is given in 8.3.5.

7.7 Extinction and decay stage

When most of the fuel in an enclosure has been consumed, or when a fuel package burns out without reaching flashover and spreading to adjacent items, the rate of burning eventually decreases.

In the absence of specific information, the heat release rate of the design fire may be taken to commence decay when 80 % of the available fire load has been consumed. The rate of decay may be taken as a linear decline over a time period, such that the integral of the heat release rate over the decay period equals the 20 % of remaining energy in the available fuel.

Further guidance on determining the decay part of the design fire curve is given in 8.8.

8 Constructing a design fire curve

8.1 Procedure

This clause applies to enclosure fires and may be modified or simplified in cases where the fire is not within an enclosure. A design fire curve for the heat release rate should be constructed using the following procedure. Note that depending on the methodology or fire model selected for the analysis, some of the steps below may be calculated by the model.

Step 1 – identify relevant parameters provided by the design fire scenario (e.g. room dimensions, size of ventilation openings, suppression system characteristics, location and type of fuel etc).

Step 2 – identify an appropriate heat release rate for the first item ignited. Either use data for individual items or use a general power law growth rate appropriate to the situation. If using individual item data, determine when (if at all) other items ignite and develop a composite design fire curve.

Step 3 – determine when flashover occurs (if at all).

Step 4 – determine the maximum heat release rate based on the available ventilation and the configuration of fuel.

Step 5 – modify the design fire curve if events occur that impact on the fire development (eg. sprinkler activation, barrier or glazing failure, manual fire-fighting, etc).

Step 6 – determine the duration of burning until the start of the decay stage.

Step 7 – determine the duration of the decay period and time of extinguishment (when the fuel is totally consumed).

Figure 3 is intended to help readers to identify and navigate the relevant parts of this document.

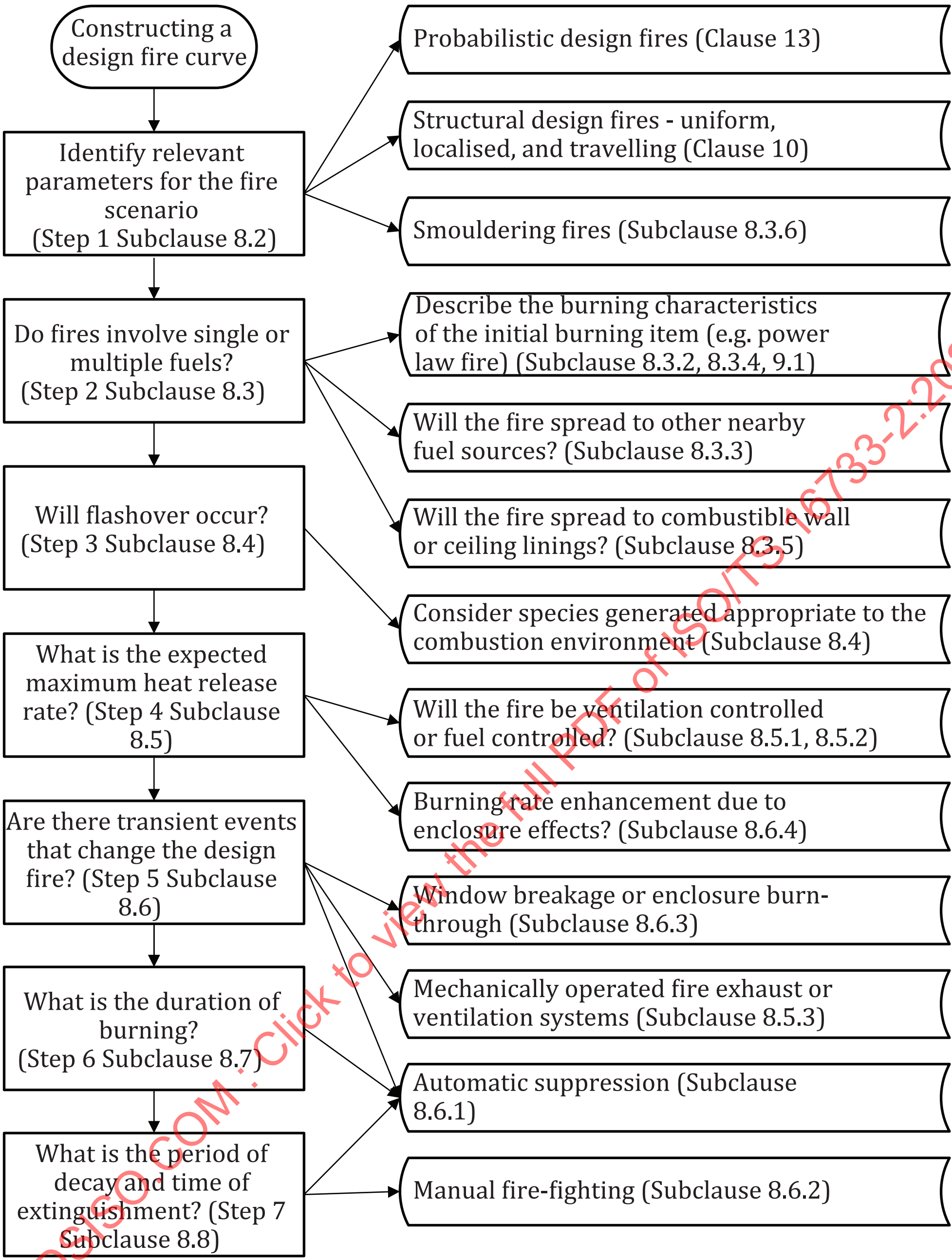


Figure 3 — Constructing a design fire curve – navigation flow chart

8.2 Step 1 — Parameters provided by the design fire scenario

Design fire scenarios can be determined from the application of ISO 16733-1.

For each of the design scenarios identified, a specific location(s) in the room or major space is also identified for that scenario. The most likely location can be identified through fire risk assessment or inferred by engineering judgment from the typical locations of the already-identified initial fuel items. The most challenging location is one where special circumstance adversely affect the performance of fire safety measures. Examples include the following:

— locations very close to room occupants (sometimes referred to as “intimate with ignition”), particularly vulnerable property, or exposed structural elements (for example, in a parking garage), such that there is insufficient time and space for fire safety measures to act effectively;

— locations in corners or other spaces where partial enclosure leads to an enhanced fire growth rate;

— locations that are shielded from fire-safety systems, or where the performance of fire safety systems can be adversely affected by the spatial configuration of the built environment, e.g. spaces with a significant ceiling height;

— locations near doorways, or other openings connecting spaces, that permit fires to spread to multiple spaces before compartmentalization provisions can effectively respond.

The criticality of the location of the design fire can also depend on the purpose of the analysis. For example:

— In a smoke control assessment of a residential corridor, a critical location for the design fire can be in closest proximity to a stair since it would increase the risk of smoke spread into the stair and therefore potentially the requirement for a higher smoke extract from the corridor;

— In an evacuation assessment of an office, a critical location of the fire can be near to the location where the exit with the highest capacity is provided or with the shortest travel distance from where the majority of occupants are;

— In a structural fire assessment of a multi-use building, a critical location of the fire can be in the areas of the building with the most onerous arrangement of fuel load and ventilation and adjacent to a critical member for the global stability of the structure (such as a transfer truss).

Once the locations of the design fires are selected, the physical parameters associated with the location can be identified, such as room dimensions, geometry and the relevant properties of the construction materials. Available ventilation due to room openings or mechanical systems and their initial status should also be identified.

8.3 Step 2 — Fires involving single or multiple fuels

8.3.1 General

When the fuel package for the design fire scenario is well-defined and unlikely to change over the design life of the built environment, then the actual burning characteristics of the fuel package can be used as the design fire.

The heat-release characteristics for a range of common items have been determined by a number of laboratories using apparatus such as the furniture calorimeter or other oxygen consumption based calorimetry[10-12]. These measurements are generally undertaken by burning the object under an instrumented hood under well-ventilated conditions. It should be noted that the rate of fire growth on objects such as upholstered furniture in actual fires within an enclosure can readily exceed that determined under free burning conditions in the open (such as under a hood). The preheating and radiation feedback from the hot layer can enhance the fire growth rate and possibly lead to under-ventilated fires with increased smoke and toxic species production. See 9.1.

The design fire can be based on the actual burning characteristics of a reference fuel package if it can be demonstrated that:

— the fire characteristics are unlikely to be exceeded during the design life of the built environment by the actual fuel package (or the probability of exceedance is acceptability small);

— the conditions under which the fire characteristics have been determined are representative of the conditions likely to exist during the design fire scenario being analysed;

— fire is unlikely to spread to other fuel packages that have not been considered.

Alternatively, when the fuel package for the design fire is not well defined or can reasonably change over the design life of the built environment, then an appropriate design fractile value from an applicable statistical distribution (if available) for variables such as fire growth rate, fire load density, etc. should be selected. In some cases, it can be appropriate to approximate the fire growth rate as a power law fire as described in 8.3.4. The use of appropriate fire models can also help to inform the rate of fire growth. See also Clause 13 if a probabilistic approach is to be used.

8.3.2 Develop the design fire curve for first item

A common approach is to describe the initial pre-flashover fire growth for a flaming fire by using a t^2 fire, assuming the energy release increases proportionally with the square of the time (see 8.3.4). This would be applicable for a reasonably large flaming ignition source. If the actual burning characteristics of a specific fuel package are to be used as the design fire, experimental data may be used for the heat-release characteristics as described in Clause 12.

In some fire scenarios, slowly developing small non-flaming fires could be a critical scenario (e.g. where sensitive electronic equipment is to be protected). Smouldering fires are discussed in 8.3.6.

8.3.3 Ignition of other items

Fire spread from the first item ignited to other nearby items should be considered, and if appropriate, included in the description of the design fire. The possibility of ignition depends mainly on the incident heat flux received and the ignitability characteristics of the target.

The incident radiant heat flux received by a nearby object due to the flames of a burning item can be calculated. The radiation received depends on the shape of the flame and its properties. Formula (1) can be used where the distance of the target from the centre of the flame is at least twice the flame diameter. It is based on uniform heat emission from a point source approximating the flame. The radiative fraction can vary from about 0,15 for low soot fuels such as methane up to about 0,6 for high soot flames such as polystyrene[13]. It also depends on the diameter of the flame and generally reduces as the diameter increases. This is due to soot blocking the radiation.

$$\dot{q}'' = \frac{X_r \dot{Q}}{4\pi c^2} \quad (1)$$

where

$\dot{q}''$ is the heat flux, kW/m²

$\dot{Q}$ is the total heat release rate, kW

X_r is the radiative fraction of the total energy (-)

c is the distance of target from the centre of the flame, m

The minimum required heat flux for the ignition of many combustible objects is typically in the range 10 – 20 kW/m². Ignition of combustible wall and ceiling linings is discussed in 8.3.5.

The surface temperature required to be reached by solid fuels for piloted ignition is typically in the range 250 to 450 °C with autoignition temperatures exceeding 500 °C. The time needed for ignition to occur depends on when these temperatures are reached which is affected by the heating characteristics and the properties of the materials and whether they are thermally ‘thin’ or ‘thick’. Indicative ignition times of thick solids are given in Table 1[13]. Other values may apply depending on the type of product.

Table 1 — Indicative ignition times of thermally thick solids [13]

Heat flux (kW/m²)	**Time** (s)	**Material**
10	300	Plexiglass, polyurethane foam, acrylate carpet
20	70	Wool carpet
20	150	Gypsum board
20	250	Wood particleboard

Table 1 *(continued)*

Heat flux (kW/m^2)	**Time** (s)	**Material**
30	5	Polyisocyanurate foam
30	70	Wool / nylon carpet
30	150	Hardboard (cellulosic)

Design fires that include the ignition of secondary items can be approximated by combining heat release rate curves for individual items offset by the time for the secondary items to ignite.

8.3.4 Power law design fire curves

In the absence of knowledge about the specific fuels present within the enclosure, for design purposes, a power law design fire may be used.

Most fires that do not involve flammable liquids, gases or light-weight combustibles, such as polymeric foams, grow relatively slowly at first. As the fire increases in size, the rate of fire growth accelerates. This rate of fire growth is generally expressed in terms of an energy-release rate. For design purposes, an exponential or power-law rate of energy release is often used. This should represent an upper bound to the large range of possible, actual fire growth rates in the scenario. The most commonly used relationship is what is known as a "t^n fire" where n = 2. In such a fire, the heat release rate is given by Formula (2):

$$\dot{Q}(t)=\alpha t^2, \quad 0\leq t<t_{gw} \tag{2}$$

where

α	is the fire growth coefficient, kW/s^2
t	is the time, s
t_{gw}	is the time at which the heat release rate reaches a maximum value, s
$\dot{Q}(t)$	is the heat release rate, kW

t^2 fires can lead to values that exceed the maximum possible heat release rate from the fuel within a given compartment. Therefore, the maximum value of $\dot{Q}$ for the heat release rate within a compartment should be limited by $\dot{Q}_{max}$, which is the lower of the values established for ventilation- or fuel-bed-controlled fires. Furthermore, in large fuel beds, the fuel first ignited can be burnt out before the last part of the fuel package is ignited. These factors should be considered.

Four categories of fire growth rate are commonly used in fire safety engineering, as indicated in Table 2. These growth rates have been derived from the growth times given in NFPA 204[14] for each category. Readers should be aware that, depending on the exact composition and configuration of the fuel, there can be a range of possible growth rates (e.g. bedding can be cotton, polyester; of various weights; lying flat or bunched up). Also, fire growth rates derived from experiments can be very dependent on the ignition source used in the experiment. Therefore, caution should be applied in using Table 2.

Table 2 — Typical fire growth categories of various fuel types

Fuel type examples	**Fire growth category**	**Fire growth rate (kW/s^2)**
Upholstered furniture or stacked furniture against combustible linings; lightweight furnishings; packing materials in piles; non-FR retarded plastic foam storage; cardboard or plastic boxes in stored vertically	Ultrafast	0,19

Table 2 *(continued)*

Fuel type examples	Fire growth category	Fire growth rate (kW/s^2)
Bedding; displays and padded workstation partitioning	Fast	0,047
Office furniture; shop counters	Medium	0,012
Floor coverings	Slow	0,003

It is necessary to consider the factors described above in the selection of the appropriate category for a scenario. Considerable engineering judgement is required in selecting the appropriate category of fire growth.

For well-defined design fire scenarios, where the geometric arrangement and type of fuel is known, the fire growth rate can be based on experimental data or numerical simulation using an appropriate flame spread model. Guidance on the rate of fire growth in stored goods may also be obtained from NFPA 204[14] and the SFPE Handbook[2]. Other useful sources of information include Mayfield and Hopkin[15] and Hietaniemi and Mikkola[16].

8.3.5 Wall and ceiling linings

Combustible wall and ceiling linings have the potential to significantly increase the rate of fire growth and the potential for flashover within an enclosure and this should be considered. It is common to assume an ignition source located within a corner as it represents a more severe exposure to the adjoining wall surfaces, producing a longer flame. If the corner flame reaches the ceiling it can spread radially outward from the corner and spread across the ceiling.

The burning characteristics of wall and ceiling lining materials may be determined using the ISO 9705-1 room corner fire test. The smoke generation from combustible wall and ceiling linings should also be considered, along with the potential for flaming droplets to occur.

Performance-based design for assessing internal surface finishes by calculation is not very common as it is more usual to refer to prescriptive codes and national requirements for these. However, if calculations are to be made, two approaches may be considered:

— represent the fire growth rate of the burning wall/ceiling by a power law design fire as described in 8.3.4;

— use a pyrolysis and flame spread model to calculate the burning surface area and heat release rate[17].

Combustible walls and ceilings can also strongly influence compartment fire dynamics in fully developed fires (e.g. unprotected or insufficiently protected mass timber construction). In these cases, caution is required as the combustible surfaces can contribute to the overall fuel load and the fire severity. Traditional approaches for specifying fire resistance ratings can not be applicable when the building structure is combustible. Design fires for structural fire engineering such as those discussed in Clause 10 can not be applicable in these cases.

8.3.6 Smouldering fires

There are at present no quantitative methods available for the prediction of potential for smouldering. It is important that consideration be given to the presence of materials that are prone to smouldering, such as upholstered furniture, bedding and cellulosic materials (particularly those treated with chemicals). It is also important that consideration be given to the presence of potential ignition sources capable of promoting smouldering, such as cigarettes, hot objects and electrical sparks.

The mass loss rate for a smouldering fire for an upholstered chair comprising cotton and polyurethane in a closed compartment was found to be represented by Formula (3)[18]. Other correlations can also be applicable.

$$\dot{m}_s = \begin{cases} 0{,}1t + 0{,}0185t^2, & 0 < t < 60 \\ 73 & 60 \le t \le 120 \end{cases} \quad (3)$$

where

$\dot{m}_s$ is the mass loss rate for smouldering combustion, g/min

t is the time, min

8.4 Step 3 — Flashover

8.4.1 General

The onset of flashover is a complex thermo-physical phenomenon that can be highly transient. Because of burning in an enclosure, a hot smoke layer develops in the upper part of the enclosure (see ISO 24678-6). Heat and mass transfer take place in the enclosure. Radiative and convective heat transfer to fuel surfaces can increase the mass loss and heat release rate. To calculate the onset of flashover, interactions between phenomena should be considered.

The general criteria for assuming the occurrence of flashover within an enclosure or room are the following[19,20]:

— 15 to 20 kW/m^2 for radiation flux from a hot upper gas layer to the floor;

— 500 °C to 600 °C for the temperature in the upper layer of gases is normally sufficient for generating the radiation flux required and is a simpler criterion, applicable to only to small/medium sized rooms.

These conditions are usually enough to increase the rate of surface flame spread and to ignite common combustible materials in a short time[21].

With respect to flashover phenomena, algebraic formulae in ISO 24678-6 may be used to estimate the threshold (minimum) heat release rate required to produce flashover in the space under consideration. These formulae are empirically developed from experiments performed in relatively small (rectilinear) enclosures of similar size and with walls and ceilings of similar thermal properties. Thus, the calculated threshold heat release rates needed to reach flashover do not incorporate many variables that complicate enclosure fires. Consequently, the calculated values should be considered as only preliminary estimates.

It should be noted that flashover is more likely for small and medium size compartments. For large compartments, fire is more likely to either remain localized (see 10.2) or progressively spread to adjacent combustible fuel (known as travelling fire, see 10.4).

8.4.2 Empirical correlations for critical heat release rate for onset of flashover

The onset of flashover is a highly complicated phenomenon and its prediction can require detailed numerical analysis. Simple correlations have been proposed for small compartments. McCaffrey's Formula (4) is often used for this purpose (see ISO 24678-6).

$$\dot{Q}_{fo} \Big/ A_o \sqrt{H} = 740 \sqrt{h_T} \sqrt{\frac{A_T}{A_o \sqrt{H_o}}} \quad (4)$$

where

$\dot{Q}_{fo}$ is the minimum heat release rate to cause flashover, kW

A_o is the area of ventilation opening, m^2

A_T is the total area of the enclosure, excluding openings, m^2

h_T is the average effective heat transfer coefficient, kW/(m^2 K)

H_o is the height of the ventilation opening, m

8.5 Step 4 — Maximum heat release rate

8.5.1 General

The maximum heat release rate of the fire inside an enclosure can generally be taken as the lesser of the fuel-controlled heat release or the ventilation-controlled heat release rate. In the case of cribs, the crib porosity can sometimes also govern the maximum heat release rate.

8.5.2 Fuel-controlled fires

Fuel-controlled fires occur less frequently than ventilation-controlled fires and can be expected only in particular situations, such as: occupancies with a high level of ventilation; very large compartments where fuel burns progressively through the compartment; or with fuel configurations where the surface area of combustibles is limited in respect to the volume of the enclosure.

The burning rate of fuel-controlled fires is dependent upon the nature and surface area of the fuel. In most practical applications, these factors are difficult to determine. For simple, well defined geometries such as timber cribs, relationships have been developed relating fuel pyrolysis rate to initial fuel mass per unit area and the remaining fuel mass per unit area [5].

The maximum heat release rate for a fuel-controlled fire can be estimated from either:

— full scale tests where the peak heat release rate can be directly measured; or

— small scale tests to determine the heat release rate per unit area for the product or material in question. The maximum heat release rate is then given by Formula (5).

$$\dot{Q}_{max} = \dot{Q}'' A_f \qquad (5)$$

where

$\dot{Q}_{max}$ is the maximum heat release rate, kW

$\dot{Q}''$ is the heat release rate per unit area, kW/m^2

A_f is the horizontal burning area of the fuel, m^2

If the mass loss rate per unit area data is provided, the maximum heat release rate is given by:

$$\dot{Q}_{max} = \dot{m}'' A_f \Delta H_{eff} \qquad (6)$$

$$\Delta H_{eff} = \chi \, \Delta H_c \qquad (7)$$

where

$\dot{m}''$ is the mass loss rate per unit area, kg/(s m^2)

ΔH_{eff} is the effective heat of combustion, kJ/kg

χ is the combustion efficiency (-)

ΔH_c is the chemical heat of combustion, kJ/kg

Heat release rate per unit area or mass loss rate per unit area data may be measured with negligible radiation feedback from the surroundings. These effects can need to be considered as discussed in 8.6.4.

Where multiple items are present, adding the respective maximum heat release rates per unit for all products and assuming all items are burning at the same time provides a conservative estimate of the maximum heat release rate.

8.5.3 Ventilation-controlled fires

The ventilation-controlled rate of burning in a compartment can be determined from consideration of air flowing into the compartment. Research has indicated[6] that the rate of air flow into a fire compartment is proportional to the ventilation factor, $\sqrt{h}$. For a compartment with a single opening and assuming the inflow and outflow are equal, the mass flow can be estimated from Formula (8).

$$\dot{m}_{out} \approx 0{,}5\, A_o \sqrt{H_o} \tag{8}$$

where

$\dot{m}_{out}$ is the rate of entry of air outflow from the enclosure, kg/s

A_o is the area of an opening, m^2

H_o is the height of an opening, m

The mass rate of fuel burning can then be estimated from the combustion reaction, since under ventilation-controlled conditions the fuel/air ratio is greater than the stoichiometric ratio. The energy release rate can be determined[7] from consideration of the effective heat of combustion of the fuel.

The above approach based on the ventilation factor underestimates fire severity in compartments with separate ventilation openings at floor and ceiling levels. It can also be inappropriate for large compartments.

Since the energy released per kg of oxygen is 13 100 kJ/kg-O_2 or 3 000 kJ/kg-air for a wide range of fuels, the ventilation-controlled heat release rate for a single opening can be estimated from Formula (9).

$$\dot{Q}_v = 1500\, A_o \sqrt{H_o} \tag{9}$$

where

$\dot{Q}_v$ is the ventilation-controlled heat release rate, kW

A_o is the area of the opening, m^2

H_o is the height of opening, m

Formula (9) gives the maximum possible heat release inside the enclosure. The actual heat release can be less if not all oxygen in the enclosure is consumed. It also ignores the fuel mass loss in the mass balance for the enclosure. Multiple openings may be represented by a single opening using the sum of the area of all the openings and the average height of the openings.

For more complicated arrangements (e.g. connected compartments) where Formula (9) is not applicable, the ventilation-controlled heat release rate may instead be derived from the available oxygen in fire plume entrained gases. This relationship is commonly adopted in multi-compartment computer zone models with a smoothing function added to account for the lower oxygen limit[22,23].

$$\dot{Q}_{\mathrm{v}} \sim \dot{m}_{\mathrm{p}} Y_{\mathrm{O2}} \Delta H_{\mathrm{O2}} \tag{10}$$

where

$\dot{m}_{\mathrm{p}}$ is the mass flow of gases entrained into the fire plume, kg/s

Y_{O2} is the mass fraction of oxygen in the plume flow, kg/kg

ΔH_{O2} is the heat of combustion based on oxygen consumption (~13,1 MJ/kg for hydrocarbons)

8.5.4 Mechanical ventilation

Fan-duct systems are commonly used in buildings for the purposes of heating, ventilation, air conditioning, pressurization and exhaust. Mechanical smoke control systems may also be provided to operate only in the event of fire. The mass flows of air/smoke should be included in smoke-filling calculations including accounting for the location/elevation of the flow inlet or outlet as well as the temperature/density of the air/smoke. It can also be important to consider the possibility of plug-holing when using a smoke extract system. Plug-holing is when fresh air is pulled into the smoke exhaust when the rate of exhaust is high relative to the depth of the smoke layer. This effect can be mitigated by increasing the number of outlets and thereby reducing the flow per outlet. As stated previously, design of smoke management systems is a specialized area and there are various design guides available to the engineer[20-22].

8.6 Step 5 — Modifying the design fire curve

8.6.1 Suppression systems

Suppression systems may be installed as part of a fire safety design requiring estimates of their response and effect on the fire development process to be determined. Suppression systems may include water-based systems such as fire sprinklers and water mist or gaseous agents using inert gases or chemical agents to suppress a fire. The following applies to common water-based fire sprinkler systems.

In scenarios where a water spray fire sprinkler system is assumed to activate, the heat release rate may be adjusted to account for the effect the sprinkler system has on the heat release rate of the fire. The maximum heat release rate can generally be taken as the heat release of the fire at the time the sprinkler activates. The response time for a sprinkler should be determined assuming a heat release rate for the growing fire as described in 8.3. Computer models are available that calculate sprinkler response time. Alternatively, a conservative estimate can be obtained from applying simple correlations for the temperature and velocity in a ceiling jet (e.g. Alpert's model).

If a suppression algorithm is intended to be used, then it is particularly important that all limitations associated with the algorithm are complied with to ensure that the water spray characteristics are sufficient for penetrating the thermal plume generated from the fire. If the effect of the sprinkler system on suppressing or controlling the fire is included in the analysis, it is also particularly important to ensure that the design of the sprinkler system is appropriate for the application and in accordance with other relevant standards. It can be necessary to explicitly consider the reliability and efficacy of the sprinkler system as part of a more general fire risk assessment.

While not precluding other approaches, this document generally recommends the following approach following activation of a sprinkler:

- when the sprinkler is predicted to activate at a heat release rate of 5 MW or higher, then the sprinklers should be assumed to have no effect on the fire development (unless experimental data supports an alternative approach);
- when the sprinkler is predicted to activate at a heat release rate of less than 5 MW, then the heat release rate should be assumed to remain constant at that level thereafter (until the fuel has been consumed).

It should also be recognized that there can be fires that do not become large enough to activate a sprinkler system but nonetheless are large enough to be hazardous to the building occupants.

8.6.2 Fire service intervention

In scenarios where fire service intervention is to be assumed then the impact of the fire service on the characteristics of the design fire will require consideration of:

- capability and training of the fire service personnel and whether fire service personnel are available at the time of the fire;
- the response time, i.e. time from being notified of a fire until fire service arrival at the fire scene;
- the time to put water (or other agent) on the fire depends on how accessible the building is for fire trucks, the nature of the access within or around the building to reach the fire location, the time required to setup, locate the fire, run hoses and apply water to the fire;

The effectiveness of fire-fighting, and the potential impact it can have on the design fire usually depends on how big the fire is at the time water (or other agent) is applied.

8.6.3 Changes in ventilation

It can be important to consider any changes in ventilation to the fire that can occur. This can be the result of occupants leaving egress doors open or closed as they leave the building; window glass breaking due to heat; parts of the building envelope burning through, providing a new source of air/oxygen. Some changes in ventilation can be by design, such as fans operating when smoke is detected, or make-up air vents being powered open, etc. The designer shall identify and document all assumptions made. If these types of change in ventilation are to be included in calculations, the designer shall carefully consider the capability of the model used and the appropriate means for including this behaviour.

8.6.4 Enclosure effects on mass loss rate of fuel

It should be noted that the rate of fire growth on objects such as upholstered furniture in actual fires within an enclosure can readily exceed that determined under free burning conditions in the open (such as under an exhaust hood). The preheating and radiation feedback from the hot layer can enhance the fire growth rate. This effect is more significant for liquid pool fires where the fuel surface area is fully exposed to the enclosure fire gases and surfaces. They can be less important for wood crib fires, where a large proportion of the fuel surface area is internal to the crib and less exposed to the enclosure surfaces. Fuels with low heat of gasification (such as liquids fuels and thermoplastic) are also more responsive to thermal feedback from the compartment compared to solids with higher heat of gasification. Enclosure feedback effects are not very important early in the fire development when the compartment temperatures are low; however, they can be very important in post-flashover fires. Additionally, the enclosure effects can become decreasingly dominant as the size of a compartment increases.

Depending on the flow characteristics through openings in the enclosure, shear mixing between the outflow and inflow can result. When some of the combustion products in the outflow are entrained back into the inflow, a reduction in the oxygen concentration of the gases feeding the flame can occur. This produces a counter effect by decreasing the mass loss rate approximately in proportion to the reduction in oxygen from ambient levels. These effects on the mass loss rate of the fuel are described by Formula (11) where the first term on the right-hand side represents the vitiated oxygen effect on the flame flux, while the second term represents the thermal feedback from the smoke and the compartment wall surfaces[24,25]:

$$\dot{m}_F = \dot{m}_{F,u}\frac{Y_{o,l}}{Y_{o,\infty}} + \frac{\dot{q}_{ext}}{L_g} \tag{11}$$

where

$\dot{m}_{F,u}$ is the mass loss rate of fuel under well ventilated free burn conditions, kg/s

$Y_{o,l}$ is the mass fraction of oxygen in the gases feeding the flame

$Y_{o,\infty}$ is the mass fraction of oxygen under ambient free-burning conditions

$\dot{q}_{ext}$ is the total external heat flux from the smoke and heated enclosure boundary surfaces, kW

L_g is the heat of gasification of the fuel, kJ/kg

8.7 Step 6 — Fire duration

8.7.1 Duration of the fire growth stage

Using the growth coefficient, α, for the growing fire as described in 8.3.4 and the maximum heat release rate, $\dot{Q}_{max}$, from 8.5, the duration of the growing fire stage for a "t^2 fire" can be given by Formula (12).

$$\tau_{gw} = \sqrt{\frac{\dot{Q}_{max}}{\alpha}} \tag{12}$$

8.7.2 Duration of the steady burning stage

The mass of fuel burned during the growth phase may then be calculated from Formula (13).

$$m_g = \int_{\tau_0}^{\tau_{gw}} \frac{\dot{Q}}{\Delta H_{eff}} d\tau = \frac{\alpha \tau_{gw}^3}{(3\Delta H_{eff})} \tag{13}$$

where ΔH_{eff} is the effective heat of combustion of the fuel (kJ/kg)

Estimate the total fuel mass from the fire load energy density (FLED, $q_{f,d}$) and the floor area (A_{fl}) from Formula (14).

$$m_{tot} = \frac{A_{fl} q_{f,d}}{\Delta H_{eff}} (\text{kg}) \tag{14}$$

Assuming 80 % of the fuel is burnt during the growth and steady burning stages, the duration of the steady burning stage may then be calculated from Formula (15).

$$\tau_s = \frac{0{,}8 m_{tot} - m_g}{\dot{Q}_{max} / \Delta H_{eff}} \tag{15}$$

8.8 Step 7 — Decay

Assuming a linear rate of decay from $\dot{Q}_{max}$ to zero, the duration of the decay stage can then be given by Formula (16).

$$\tau_d = \frac{0,4 m_{tot} \Delta H_{eff}}{\dot{Q}_{max}} \qquad (16)$$

9 Species production

9.1 Species yields

Species yields from burning materials depends on the material composition and on the combustion environment (air supply) and the presence of fire retardants or chemical agents in the fuel. In cases where the air supply is restricted, combustion is incomplete and higher yields of products such as CO and soot are produced in preference to CO_2. Many data values given in the literature are applicable to well ventilated flaming fires and are not appropriate for ventilated-limited or post flashover fires.

Generation of combustion products in the form of species are typically specified as a yield defined as the mass of species *i* produced per mass of fuel burned. The most common species considered in fire safety engineering are soot (see Table 3) and carbon monoxide (see Table 4). However, other species such as water vapour, carbon dioxide and hydrogen cyanide can also be of interest. Further information on species yields can be found in the literature[26] along with its application to fire safety engineering[3].

The determination of species, their concentrations and quantities may be required as a source term in the case where the consequences of the fire and its impact on people and the external environment are to be assessed. In this case appropriate data should be used and its validity checked.

Table 3 — Suggested yield of soot

Material	**Well-ventilated flaming fires** **Soot yield** (g/g)	**Well-ventilated smouldering fires** **Soot yield** (g/g)	**Under-ventilated fires**
Cellulosic	0,01-0,025 [15]	0,01-0,17 [15]	—
Plastics	0,01-0,17 [15]	0,01-0,19 [15]	—
Mixed fuel from Ref [27]	0,07	—	0,14

Table 4 — Suggested yield of CO

Material	**Well-ventilated flaming fires** **CO yield** (g/g)	**Well-ventilated smouldering fires** **CO yield** (g/g)	**Under-ventilated and post-flashover fires**
Cellulosic	0,2 [20]	0,5 [3]	0,3 [20]
Mixed fuel from Ref [27]	0,04	—	0,4

10 Design fires for structural fire engineering

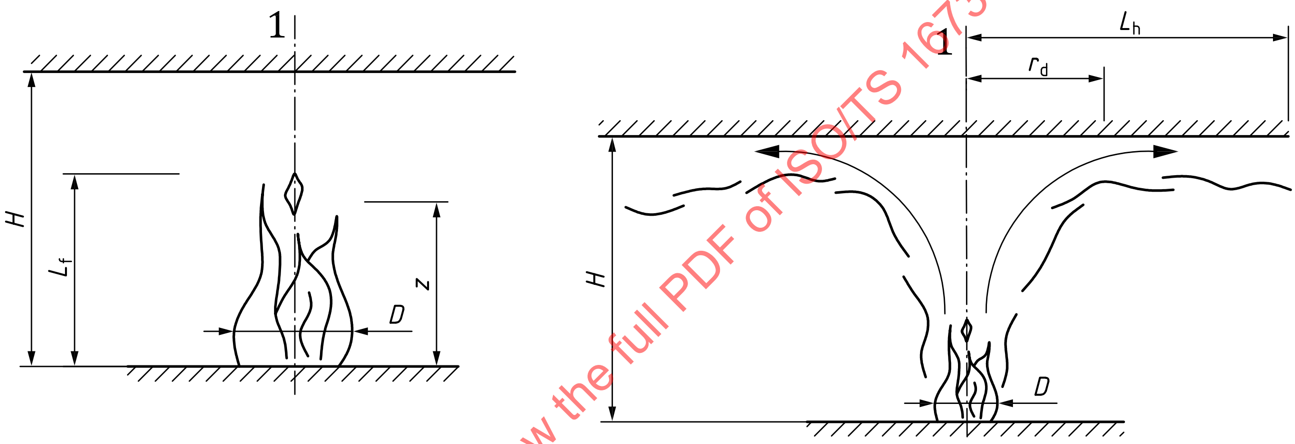
10.1 General

An overview of the most commonly used design fires (noting that the review is not exhaustive) for the purposes of structural fire analysis is presented here. This subclause only describes fire scenarios/models that are relevant to the conventional building environment (office, residential, stadiums, arenas etc). As a result, different types of fires that could occur in other structures in the built environment (such as tunnels, bridges, etc.) are not covered here.

Furthermore, the contents of this clause give design fires in terms of deterministic relationships for temperature and heat fluxes due to their current prevalence. It is recognized that structural design fires could also be described in terms of the underlying fire loads, ventilation and heat release within enclosures. It is not intended for this document to preclude the use of these alternative approaches.

10.2 Localized fires

A localized fire can be considered where flashover is unlikely to occur, and a travelling fire is not possible. Depending on the fire size and the dimensions of the compartment, a localized fire can or can not impinge on the ceiling of the compartment. Various localized fire models have been published in the literature. Currently, the most widely used are those of EN 1991-1-2:2002[35] to determine when flames do not impinge the ceiling (such as a bin fire in an airport or an open-air fire) and when they do impinge the ceiling (such as in a car park). These two cases are illustrated in Figure 4. These models have been derived from experimental tests and therefore are semi-empirical.



a) Flame does not impinge the ceiling **b) Flame impinges the ceiling**

Key

1 flame axis

D diameter of the fire (m)

z height along the flame axis (m)

L_f vertical flame height (m)

L_h horizontal flame length (m)

H vertical distance between the fire source and the ceiling (m)

r_d horizontal distance between the vertical axis of the fire and the point along the ceiling where the thermal flux is calculated (m)

Figure 4 — Flame impinging and not impinging the ceiling[35]

10.2.1 Flames not impinging the ceiling

For fires not impinging the ceiling of a compartment, the following method can be used to determine the temperature in the fire plume as a function of height. The flame height can be calculated using ISO 16734.

The temperature in the plume along the vertical flame axis is given by Formula (17), taken from EN1991 -1-2:2002, Annex C[35].

$$\Theta_{(z)} = \min\left(20 + 0{,}25\,\dot{Q}_c^{\frac{2}{5}}\left(z - z_o\right)^{-\frac{5}{3}}, 900\right) \text{°C} \quad (17)$$

with $z_o = -1{,}02\,D + 0{,}00524\,\dot{Q}^{2/5}$

where

$\dot{Q}$ is the total heat release rate, W

$\dot{Q}_c$ is the convective part of the heat release rate, typically between 0,66Q *to* 0,8Q, W

z is the height along the flame axis, m

z_o is the virtual origin of the axis, m

The equations are recommended for a diameter of the fire $D \leq 10$ m; and the heat release rate of the fire $Q \leq 50$ MW.

10.2.2 Flames impinging the ceiling

The following is one model that can be used to determine the heat flux received by the ceiling surface area level when flames impact the ceiling. Other formulae[28] may also be used where applicable to the design. The horizontal flame length, L_H, can be determined from Formula (18).

$$L_H = 2{,}9H\left(\dot{Q}_H\right)^{0{,}33} - H \quad (18)$$

with

$$\dot{Q}_H = \frac{\dot{Q}}{1{,}11 \times 10^6\ H^{2{,}5}}$$

where

L_H is the horizontal flame length, m

H is the vertical distance between the fire source and the ceiling, m

$\dot{Q}_H$ is a non-dimensional heat release rate

$\dot{Q}$ is the total heat release rate of the fire, kW

The heat flux h' (W/m^2) received at a distance r from the flame axis at ceiling level can be determined from Formula (19).

$$h' = \begin{cases} 100\ 000 \text{ for } y \leq 0{,}30 \\ 136\ 300 - 121\ 000y \text{ for } 0{,}30 < y < 1{,}0 \\ 15\ 000\, y^{-3{,}7} \text{ for } y \geq 1{,}0 \end{cases} \quad (19)$$

with

$$y = \frac{r_\text{d} + H + z'}{L_\text{H} + H + z'}$$

where

r_d is the horizontal distance from the vertical flame axis to the point along the ceiling where the thermal flux is calculated, m

z' is the vertical position of the virtual heat source, see Formula (20)

y is the dimensionless constant

$$z' = 2{,}4D\left(\dot{Q}_D^{2/5} - \dot{Q}_D^{2/3}\right) \text{ when } \dot{Q}_D < 1 \quad (20)$$

$$z' = 2{,}4D\left(1 - \dot{Q}_D^{2/5}\right) \text{ when } \dot{Q}_D \geq 1$$

where

$$\dot{Q}_D = \dot{Q} / \left(1{,}11 \cdot 10^6 - H^{2{,}5}\right)$$

The net heat flux at ceiling level, h'_net, can be determined using Formula (21).

$$h'_\text{net} = h' - \alpha_c\left(\theta_\text{m} - 20\right) - \Phi \varepsilon_\text{m} \varepsilon_\text{f} \sigma \left[\left(\theta_\text{m} + 273\right)^4 - 293^4\right] \quad (21)$$

where

α_c is the convective heat transfer coefficient

ε_f is the emissivity of the fire

ε_m is the surface emissivity of the member

Φ is the configuration factor (= 1 when ceiling is exposed to flame)

θ_m is the surface temperature of the member, °C

σ is the Stefan Boltzmann constant

10.3 Parametric fires

One of the most popular fully developed design fire models used in structural fire engineering is the EN 1991-1-2 parametric fires based on the concept of heat balance inside a compartment.

The method assumes that a fully developed fire will develop in a compartment (i.e. temperatures will be relatively uniform) and that the fire is either ventilation-controlled or fuel-controlled and that the fire lasts as long as fuel is still available within the compartment (burnout). The parametric fire model takes into account the compartment size, fuel load, ventilation conditions and the thermal properties of compartment walls and ceilings.

The parametric curves are applicable when the flow of hot gases in and out of the enclosure is controlled by openings (vents) in the walls of the enclosure. Hence, they are not applicable to enclosures with significant flow through horizontal openings in floors or ceilings.

EN 1991-1-2 limits the application of the parametric fires to compartments with a floor area of up to 500m^2, without openings in the roof, a maximum compartment height of 4m and compartments with mainly cellulosic type fire loads. There are also limits on the thermal absorptivity of the enclosure surface, opening factor and the fire load density.

The parametric fire curves have two distinct phases:

1) A heating phase where the gas temperature rises with the increase of time.

2) A cooling phase. A linear slope is assumed for the cooling phase of the fire.

10.3.1 Heating phase

During the heating phase of a fire, the parametric fire curve (Θ_g) is given by Formula (22).

$$\Theta_g = 20 + 1325\left(1 - 0{,}324e^{-0{,}2t'} - 0{,}204e^{-1{,}7t'} - 0{,}472e^{-19t'}\right) \quad (22)$$

where

Θ_g is the parametric fire gas temperature, °C

e represents the mathematical constant - Euler's number

The parametric time (in hours) is given by Formula (23).

$$t' = t\,\Gamma \quad (23)$$

With the dimensionless ventilation parameter given by Formula (24):

$$\Gamma = \frac{(O/b)^2}{(0{,}04/1160)^2} \quad (24)$$

In case of $\Gamma = 1$ the equation approximates the standard temperature-time curve.

The thermal inertia of linings (for an enclosure surface with single layer of material) can be given using Formula (25):

$$b = \sqrt{\rho_b c_p \lambda} \quad (25)$$

with the following limits: $100 \le b \le 2\,200$ J/(m^{2}s$^{1/2}$K)

where

b is the thermal inertia of linings, J/(m^{2}s$^{1/2}$K)

The density ρ_b, the specific heat, c_p, and the thermal conductivity, λ, of the boundary may be taken at ambient temperature.

When multiple materials are present in an enclosure, the thermal inertia of the enclosure is determined by considering the combined effect of different thermal inertia in walls, ceiling and floor (see BS EN 1991-1-2 for more details), using Formula (26):

$$b = \frac{\Sigma b_j A_j}{A_t - A_o} \tag{26}$$

where

b_j is the thermal inertia of the jth boundary lining material

A_t is the total area of enclosure (walls, ceiling and floor, including openings), m^2

A_o is the opening area, m^2

The opening factor, O, can be determined using Formula (27):

$$O = \frac{A_o \sqrt{H_o}}{A_t} \tag{27}$$

where

O is the opening factor, m$^{1/2}$

A_t is the total area of enclosure (walls, ceiling and floor, including openings), m^2

with the following limits: $0,02 \leq O \leq 0,20$ m$^{1/2}$. Note that national application documents of different countries in Europe may sometimes amend these values.

10.3.2 Heating duration and maximum temperature

The maximum temperature Θ_{max} in the heating phase happens for $t' = t'_{max}$ [see Formula (28)]

$$t'_{max} = t_{max} \tag{28}$$

With $t_{max} = \max\left[\left(0,210^{-3} q_{t,d} / O\right); t_{lim}\right]$ and $q_{t,d} = q_{f,d}\ A_f \ / \ A_t$ where $50 \leq q_{t,d} \leq 1\,000\left(\text{MJ/m}^2\right)$.

where

$q_{f,d}$ is the design value of the fire load density related to the surface area of the floor, A_f

t_{lim} is the limiting time, h

Note that t_{lim} needs to be input in hours in the above equation. t_{lim} is 25 min in case of slow fire growth rate, 20 min in case of medium fire growth rate and 15 min in case of fast fire growth rate.

When $t_{max} = t_{lim}$, the fire is fuel-controlled and not ventilation-controlled. In this case, instead of Formula (6), Formula (29) needs to be used to calculate the time:

$$t' = t\Gamma_{lim} \tag{29}$$

where

$$\Gamma_{lim} = \frac{(O_{lim}/b)^2}{(0,04/1160)^2} \tag{30}$$

$$O_{\text{lim}} = 0{,}1 \times 10^{-3} \frac{q_{\text{t,d}}}{t_{\text{lim}}} \quad (31)$$

In case of (O > 0,04 and $q_{\text{t,d}}$ < 75 and b < 1 160), Γ_{lim} shall be multiplied by factor k given by the Formula (32):

$$k = 1 + \left(\frac{O - 0{,}04}{0{,}04}\right)\left(\frac{q_{\text{t,d}} - 75}{75}\right)\left(\frac{1160 - b}{1160}\right) \quad (32)$$

10.3.3 Cooling phase

Linear temperature-time curves for the cooling phase after the heating phase of parametric fire curves are given in Formula (33).

Depending on the value of t'_{max} three different linear curves for gas temperature Θ_{g} are defined as follows:

$$\Theta_{\text{g}} = \begin{cases} \Theta_{\text{max}} - 625\left(t' - t'_{\text{max}} x\right) \text{ for } t'_{\text{max}} \le 0{,}5 \\ \Theta_{\text{max}} - 250\left(3 - t'_{\text{max}}\right)\left(t' - t'_{\text{max}} x\right) \text{ for } 0{,}5 < t'_{\text{max}} < 2 \\ \Theta_{\text{max}} - 250\left(t' - t'_{\text{max}} x\right) \text{ for } t'_{\text{max}} \ge 2 \end{cases} \quad (33)$$

where

$$t_{\text{max}} = \left(0{,}2 \times 10^{-3} q_{\text{t,d}} / O\right)\Gamma \quad (34)$$

With:

$x = 1{,}0$ if $t_{\text{max}} > t_{\text{lim}}$ or

$x = t_{\text{lim}} \Gamma / t'_{\text{max}}$ if $t_{\text{max}} = t_{\text{lim}}$

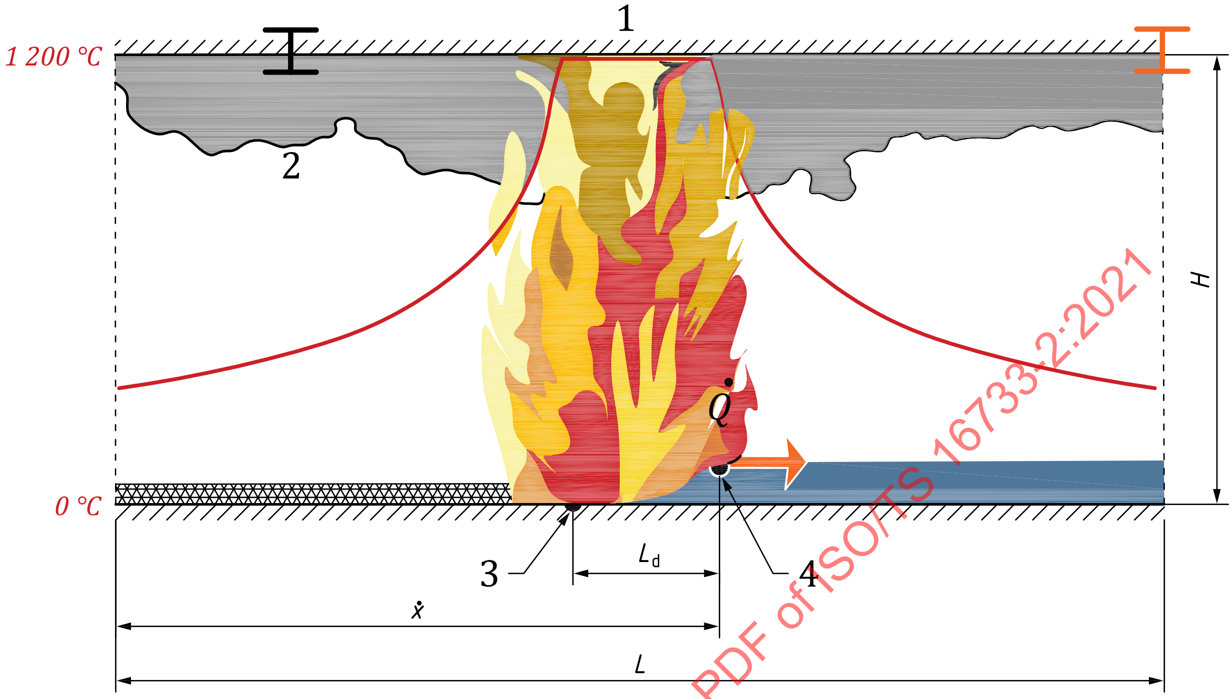
10.4 Fires in large compartments (travelling fires)

In very large compartments flashover may not occur and fire tends to travel rather than burn uniformly and simultaneously. In large compartments, fire dynamics are expected to be limited by fuel and be less influenced by the thermal inertia of the linings since the fire will be generally more remote from walls and openings. Several previous studies[29-31] assessing the structural fire response of buildings under uniform and travelling fires have demonstrated that travelling fires can be onerous for the structure given that they can produce different thermal and structural responses compared to uniform fires. As a result, researchers have put forward methodologies for representing the effects of travelling fires for structural fire design purposes (such as Reference[32]).

The exposure is idealized for structural fire design purposes with the aim of removing complexities and simplifying its use, but equally capturing the key phenomena experienced by non-uniform fires.

A major concept behind the travelling fire methodology (TFM) is that the fire induced field is split for a compartment (over the longest direction into two regions), into the near-field (flames) and the far-field (smoke). This results in the generation of spatially non-uniform and transient temperature curves for the whole floor as shown in Figure 5. The near-field represents the burning region of the fire where the flames directly impinge on the ceiling and assumes the peak flame temperatures. The far-field represents the region remote from the burning area where the structure is mainly heated by hot smoke moving away from the fire source.

The available TFMs are flexible in allowing any available or future correlation to be used to describe the near-field or far-field temperature depending on the complexity and accuracy required.



Key

1 near field
2 far field
3 trailing edge
4 leading edge
burnt out fuel
unburnt fuel
fire spread, s
gas temperatures

Figure 5 — Illustration of a travelling fire and distribution of gas temperatures

The travelling fire concept can consider a range of possible fire dynamics by covering a wide range of fire sizes depending on the fire coverage (A_f) of the total floor area. The TFM typically assumes a rectangular shape of the floor plate/compartment and therefore a fire can be characterized in a form, F_s, using Formula (35):

$$F_s = \frac{L_d}{L} \text{ or } \frac{A_f}{A} \tag{35}$$

TFM assumes a uniform fuel load across the fire path, $q_{f,d}$ (kJ/m^2), and a constant heat release rate per unit area $\dot{Q}''$ (kW/m^2). Based on a given burn area, A_f (m^2), the total heat release rate can then be calculated using Formula (36):

$$\dot{Q} = A_f \dot{Q}'' \tag{36}$$

Therefore, as the fire spreads, according to Formula (37), each fire area would have a constant burning time of:

$$t_b = \frac{q_{f,d}}{\dot{Q}''} \tag{37}$$

In the methodologies currently available, fire is assumed to spread at a constant fire spread rate, *s*, along a linear fire path (other fire paths are possible and can be expressed in similar ways). For linear fire spread, the speed can be defined using Formula (38):

$$s = \frac{L_d}{t_b} \tag{38}$$

For a linearly travelling fire, the total burning time can then be calculated using Formula (39):

$$t_{tot} = t_b \left(\frac{1}{F_s} + 1 \right) \tag{39}$$

As a result, smaller fires experience longer burning duration compared to larger fires. The total burning time has a major influence in the final temperature of protected steel and concrete structures.

For the near field, the concept of the flapping angle[32] has been introduced which assumes that structural members will actually experience lower average gas temperatures rather than the peak flame temperatures observed in fires. Based on this work, the flapping length can be determined using Formula (40):

$$f = L_d + 2H \tan\left(f_a \frac{\pi}{180} \right) \tag{40}$$

The reduced average near-field temperature can then be determined using Formula (41)-(46):

$$T_f = T_a + \frac{T_{nf}\left(2r_{x1} + L_d\right) - 2T_a \cdot r_{x2}}{f} + \frac{32{,}28\dot{Q}^{2/3}}{H \cdot f}\left(r_2^{1/3} - r_{x2}^{1/3}\right) \tag{41}$$

where

$$r_2 = \frac{f}{2} \tag{42}$$

$$r_{x1} = \max\left(0, r_0 - L_d/2\right) \tag{43}$$

$$r_{x2} = \max\left(L_d/2, r_0\right) \tag{44}$$

$$T_{nf} = 1200 \tag{45}$$

$$r_0 = \left(\frac{5{,}38}{H(T_{nf} - T_a} \right)^{3/2} \tag{46}$$

where

T_f is the reduced near-field temperature due to flapping, °C

T_a is the room temperature, °C

T_{nf} is the near-field temperature, °C

r_x is the radial distance away from the fire, m

L_f is the vertical flame height, m

H is the vertical distance between the fire source and the ceiling, m

f is the flapping length of the flame

In the TFM the flapping angle of ±6,5° is typically assumed.

Reference [32] proposes a simple to use analytical expression incorporating the Alpert's equation and the far-field temperatures can be determined using Formula (47). Compared with other available solutions, Alpert's correlation provides results within the acceptable limits of accuracy and, therefore, was chosen for simplicity.

$$T_{max}(x,t)=\begin{cases} T_\infty + \dfrac{5{,}38}{H}\left(\dfrac{L\,L_t^*\,W\,\dot{Q}''}{\left|x+0{,}5\,L\,L_t^*-\dot{x}_t\right|}\right)^{2/3} \\ T_{nf},\ \text{if} \begin{cases} T_{ff}>T_{nf}\,; \\ \left|x+0{,}5\,L\,L_t^*-\dot{x}_t\right|\le 0{,}5L_d \end{cases} \end{cases} \tag{47}$$

$$\text{for } \dot{x}\le L \rightarrow \dot{x}_t=s\cdot t;\ L_t^*=\min\left[L^*,(s\cdot t)/L\right]$$

$$\dot{x}>L \rightarrow \dot{x}_t=L;\ L_t^*=1+(L_f-s\cdot t)/L$$

where

L is the length of the compartment, m

W is the width of the compartment, m

An alternative approach of the travelling fire considering the flame extension under the ceiling can be found in Reference [33].

11 External design fires

There are two types of fires involving direct flaming exposure that can harm the external surface (or façade) of a built environment: fires originating within the built environment and those originating outside it. An example of the former is when flames from a fully developed internal fire issue from an opening and thereafter transfer heat to an external surface (or façade). An example of the latter is when flames from a fire in miscellaneous storage or waste adjacent to the built environment transfer heat to the external surface. In both cases, flame heat transfer can lead to ignition of combustible content in the external surface and subsequent sustained flame spread. This can cause considerable damage to the external wall and lead to propagation of fire to the interior via openings in the external envelope at locations and distances remote from the original source fire. In addition, flames from a fire in an adjacent built environment can expose an external surface with convective and radiant heat, again leading to ignition of combustible content in the external surface and subsequent sustained flame spread.

Generally, the highest imposed total heat transfer from flames to external surfaces, and, therefore, the greatest risk of damage or sustained flame spread, occurs as the result of fire sources outside and adjacent to the external surface. It is important to select an external design fire that is representative of the maximum heat-flux exposure to be expected from the design fire scenario of concern.

Flames issuing from an opening in the external surface of a built environment can be characterized by a heat flux profile on the external surface along the length of the flame. The jet of flame issuing from a window of a compartment fully involved in fire can be characterized by the flame length and the temperature along the jet. Expressions have been derived for both of these variables and are in use in some national codes[34,35]. A recent review of the literature and the available correlations for flame length and heat flux on the wall above window openings is available[36].

12 Fire tests

In some cases, engineering calculation methods are not available, e.g. for estimating fire growth in complex material systems or for estimating the response of a given fire to proposed protection systems, such as sprinklers, because of the complexity of the interactions involved. For such cases, the only way to predict the outcome of a given scenario is to make use of one or more reference-scale test methods or ad hoc test methods developed for the purpose. This type of test method is intended to represent a possible "real" fire situation by exhibiting a wide range of "real" fire phenomena in a full-scale geometry while maintaining a well-defined, well-documented and well-controlled test environment.

Reference-scale test methods are used either directly, to evaluate specific trial design strategies, or indirectly, to evaluate the accuracy of a particular engineering calculation method which, if found to be suitable, is then used to evaluate a range of design strategies. In all cases, proper interpretation of results from reference-scale test methods is particularly important to ensure validity for the particular design application. For example, if a reference-scale test environment is used to evaluate a trial sprinkler protection strategy in a warehouse, it is important that the test results be analysed to verify that the success of fire protection is not influenced by factors, such as oxygen depletion, that might not be present during an actual fire.

Fire tests may also be conducted to measure important design fire parameters for a fuel package, such as the heat release rate, with the intention of inputting the results to a computer model for evaluating subsequent fire behaviour and hazardous conditions. The engineer should consider any possible effects of the room size and lining materials that differ from the test environment, especially for thermal feedback and oxygen depletion effects that could result in a different heat release rate in the actual fire situation.

In some cases, it is necessary to employ a combination of test results and calculations. Generally, the efficiency of the calculation method is determined by assessing the results of the test, and a calculation is performed for the real-case scenario, taking into account a safety factor to deal with the accuracy of the method obtained in the comparison with the test results.

13 Probabilistic aspects of design fires

13.1 General

Given the inherent randomness of fire starts and initial conditions and the nature of some of the factors affecting the development and severity of fire, a probabilistic analysis should always be considered. This section provides an overview of selected probabilistic analysis methods, relating to design fires. More detailed guidance on fire risk assessment and probabilistic analysis is provided in ISO 16732.

In general, probabilistic approaches treat selected design fire input and output parameters as ranges of statistically distributed values, instead of the single fixed values typically used in deterministic approaches. In addition, the impact of fire protection measures (e.g. a sprinkler system) can be accounted for based on the probability of their successful operation (reliability) and efficacy. The objective for the use of such an approach in performance-based design is typically to account for the variability and/or uncertainty in the input parameters and to investigate their impact on fire severity, smoke production and other important characteristics of fire development.

The approaches by which design fires can be incorporated into probabilistic analysis include:

— inclusion of statistical representativeness/distribution characteristics to important input parameters;

— simulations using distributed input and sampling methods;

— stochastic models;

The first two approaches use deterministic equations to address the fire phenomena and introduce the probabilistic element through input parameters. In contrast, the third group treats the fire phenomena, fully or partially, as a stochastic process with lesser or no use of deterministic approximations (equations).

13.2 Inclusion of statistical representativeness/distribution characteristics

Inclusion of statistical representativeness characteristics of important input parameters is a relatively simple manner of explicit probability treatment. However, in a majority of cases it is only partial. This approach is similar to the worst credible scenario approach. However, an explicit quantification of parameter representativeness is provided. It should be pointed out that the statistical representativeness relates only to the parameter(s) in question rather than the design fire as a whole. For example, the assumed fire load density may be taken as representative of 90 % cases (90th percentile) for the occupancy in question. However, even if one of the input parameters is selected as the upper 90th percentile value, the design fire as such does not necessarily represent 90 % of the fires in the given occupancy type, as the fire is affected by further parameters, such as fuel configuration and ventilation, etc. The value for these other parameters can also be selected from a representative statistical distribution. On the other hand, selecting most or all input parameters from upper extreme intervals can result in an overly severe fire with a very low probability of occurrence.

13.3 Simulations using distributed input and sampling techniques

In general, this group of methods includes more or less any combination of distributed input parameters (statistically or arbitrarily), a sampling method (Monte Carlo, Latin hypercube, etc.) and a deterministic simulation algorithm (zone, CFD or other type of fire model). Such an approach addresses more appropriately the variability and uncertainty in input parameters which can cause difficulties in identification of one representative value for each input parameter when using the deterministic representation of a design fire. In general, the representativeness of the results increases with the number of sampled input points.

In relation to design fires, these methods can be used to account for variability and/or uncertainty of input parameters, for example fire growth rate, or the random nature of certain input parameters, such as spatial configuration of fuel items. The higher number of runs, each with uniquely sampled input variables, the higher the accuracy/representativeness of the simulation results, assuming the variability and uncertainty in the input parameters is addressed correctly. Due to the high number of repetitions, required software tools are used to carry out such types of simulations. The main drawback can be a high computational time demand, especially when advanced fire models are employed, e.g. CFD models.

Monte Carlo employs repeated random sampling from predefined input variable sets or distributions, which are then used in calculation algorithms. Subsequently, results are aggregated, and their respective distributions analysed.

Latin hypercube divides the cumulative distribution function/curve into *n* equal intervals and draws randomly from these intervals; each from the intervals is randomly sampled the same number of times. This sampling technique reduces the number of samples required for the results to start converging in comparison to Monte Carlo sampling.

Various analysis tools developed using these techniques are found in the literature[37-39].

13.4 Stochastic models

Stochastic models can approximate the design fire in various ways, depending on how they address the evolvement of random quantities in time and/or space, and if and how they incorporate deterministic representation of the underlying fire physics, chemistry and thermodynamics. In general, stochastic models involve rather complex calculations and potentially with a great number of repetitions. Therefore, they are not used in a simple hand-calculation format. In addition, the required probability values and distributions are often difficult to source or derive; hence, some of the approaches presented have a rather narrow field of application. Due to the complexity of this topic, this section is limited to a brief overview of the modelling approaches available in relation to the design fire. Stochastic fire models are based on the following stochastic processes[40]:

— Random walk;

— Markov models – chains and processes;

— Network models – branching processes;

— Stochastic differential equations;

The representation of the design fire depends on the type of the stochastic fire model. It ranges from a set of discrete probabilities associated with the fire attaining a specific growth phase, through spatial fire spread, to the prediction of the actual heat release rate in time. As with deterministic design fire models, the selection of the approach depends on the complexity of the task at hand and the level of detail required.

The *Random walk model* treats the fire process, or a part thereof, as a series of random steps governing its development. A random step is made every short period and this step represent either fire propagation or extinguishment/burn out. The fire propagation step is assigned a probability, p_{fp}, and the fire extinguishment step is assigned a probability, p_{fe}, and since there is no other step possible, $p_{\mathrm{fp}} + p_{\mathrm{fe}} = 1$. By defining the step of a random walk, for example, this basic approach can be adapted for the prediction of probable fire duration, heat release rate, area damaged, etc. The fire can grow until extinguishment occurs or all available fuel has been consumed. The step probabilities p_{fe} and p_{fp} are not constant values in reality and they change with the course of fire. More details on random walk model can be found in the literature[41].

The *Markov model* is a stochastic model treating the stages of fire growth as states, phases or realms[42,43]. At each time interval (e.g. a minute), the probabilities of the fire being in any of the states are updated through the state transition probabilities as the duration of the fire progresses. Given the nature of the Markov process (a memoryless process), the transition probability is not affected by the past behaviour, i.e. the probability of the fire progressing into another state is not affected by its duration or the number of state changes that have already occurred.

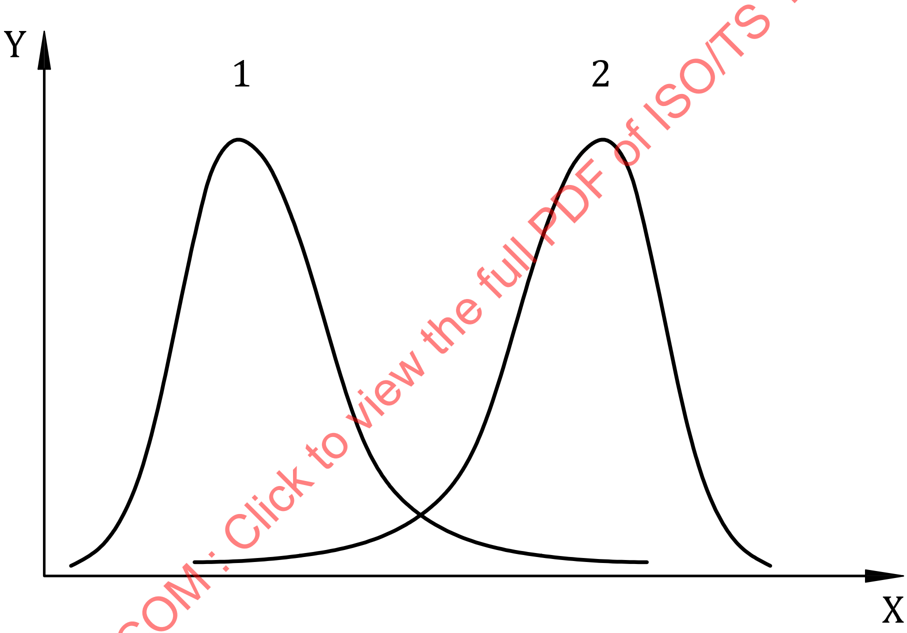
A common set of states was proposed by Berlin[44] with six states defined as realms for residential occupancies: no-fire state, sustained burning, vigorous burning, interactive burning, remote burning and full room involvement. The realms were defined by critical events characterized by heat release rate, flame height and upper room gas temperature.

Network models are more advanced stochastic models which take into account the time-dependence of state transition probabilities and spread of fire within the built environment[45,46]. Network models are more appropriate for stochastic simulation of spatial fire spread than Markov models, as rooms, corridors, etc. are modelled as nodes of a fire spread network which is then turned into a probabilistic network. There can be multiple ways of fire spread between the nodes as well as fire growth within a node itself. Network models consider fire spread between two given rooms by breaching compartment boundaries (after reaching a flashover state) or along multiple virtual divisions of a larger space (e.g. a corridor). Fire growth and fire spread are represented by links, each associated with a probability of the fire taking the path; more advanced models pair the link's portability with the time it takes for the fire to complete the spatial or phase transition.

Stochastic differential equations are a modelling approach in which the deterministic differential equations representing fire phenomena are transformed into stochastic differential equations by replacing one or more terms by a stochastic process; this is also known as the introduction of random perturbations. By doing so, uncertainties and variability associated with many input parameters are accounted for and the output variables exhibit similar behaviour (fluctuations) as in real fire situations.

13.5 Results of probabilistic analysis and their evaluation

The results of a probabilistic analysis take a form of a statistical distribution or a discrete value associated with a probability or percentile. Such results may be evaluated on an absolute or equivalence-based acceptance criteria basis. An example of acceptance based on absolute criteria is the comparison of design hazard and performance distributions, for example stress vs. strength, required safe egress time (RSET) vs. available safe egress time (ASET), etc. If the overlap of the top design hazard and bottom performance percentiles is sufficiently small, or if there is no overlap, the design is considered acceptable. In the case where RSET and ASET are both random variables represented by probability distributions, the overlap area between the two curves in Figure 6 is an indicator of the probability of failure.



Key

X time

Y probability

1 RSET

2 ASET

Figure 6 — Probability versus time for two random variables

The reliability calculation considers the combinations of all the values assumed by the two random variables, ASET (x) and RSET (s). The probability of ASET being larger than RSET is given in Formula (48)[47]:

$$\Pr(x>s)=\int_{-\infty}^{\infty} f_S(s)\left[\int_{s}^{\infty} f_X(x)\,dx\right]ds \tag{48}$$

where

$f_s(s)$ is the probability distribution for RSET

$f_s(x)$ is the probability distribution for ASET

An equivalence-based approach assumes acceptance when the performance of the engineered design is the same or better than the prescriptive one. Usually, the level of risk is compared (e.g. a comparison of the probabilities of fire fatality, compartment boundary, or structural member failure). Further guidance and examples of the interpretation of probabilistic analysis results can be found in ISO 16732-1 and ISO 16732-2.

14 Documentation

ISO 23932-1 requires the documentation of the selection of engineering methods used for evaluation in a fire safety design report. The report is required to present enough detailed information to allow its evaluation in terms of meeting the FSOs when assessed against design scenarios identified using ISO 16733-1 and the associated design fires from application of this document. The exact form of documentation (reporting) may vary by jurisdiction and by project.

