PD 7974-1:2019

BSI Standards Publication

Application of fire safety engineering principles to the design of buildings

Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)

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Publishing and copyright information

Published by BSI Standards Limited 2019

ISBN 978 0 580 97726 8

ICS 13.220.20; 91.040.01

The following BSI references relate to the work on this document:
Committee reference FSH/24
Draft for comment 18/30373549 DC

Amendments/corrigenda issued since publication

Date	Text affected

Contents

Summary of pages

This document comprises a front cover, and inside front cover, pages i to iv, pages 1 to 41, an inside back cover and a back cover.

Foreword

This part of PD 7974 is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 March 2019. It was prepared by Technical Committee FSH/24, *Fire safety engineering*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This part of PD 7974 supersedes PD 7974-1:2003, which is withdrawn.

Relationship with other publications

This Published Document is one of a series of documents published under the Fire Standards Policy Committee, and is a supporting document to BS 7974, *Application of fire safety engineering principles to the design of buildings — Code of practice*.

Other parts in this series, PD 7974, include:

Part 2: Spread of smoke and toxic gases within and beyond the enclosure of origin (Sub-system 2)

Part 3: Structural response and fire spread beyond the enclosure of origin (Sub-system 3)

Part 4: Detection of fire and activation of fire protection systems (Sub-system 4)

Part 5: Fire and rescue service intervention (Sub-system 5)

Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6)

Part 7: Probabilistic risk assessment

Information about this document

This is a full revision of the document, and introduces the following principal changes:

- consolidation of all principal design fire development considerations into sub-system 1 which are subsequently called upon as an input for other sub-systems (e.g. 2 and 3);
- greater clarity regarding the phases of fire development;
- design correlations that logically follow a conventional fire timeline of events;
- where practicable, explicit acknowledgements of the inherent assumptions underpinning design correlations;
- further generalization of design approximations for growing fires;
- revised correlations with respect to ignition, heat flux from localized fires, pre-flashover compartment fire temperatures, and sprinkler-controlled fires;
- the introduction of a travelling fire framework for fully developed fires that might not develop to flashover
- improved reference data for smoke and toxic gas yields; and
- removal of some reference data as it is either too generalized or out of date.

Use of this document

As a guide, this part of PD 7974 takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

This publication is not to be regarded as a British Standard.

Presentational conventions

The guidance in this Published Document is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is “should”.

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. “organization” rather than “organisation”).

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a Published Document cannot confer immunity from legal obligations.

Introduction

This Published Document is one of a series of documents intended to support BS 7974. The Code of Practice provides a framework for developing a rational methodology for design using an alternative fire safety engineering approach through the application of scientific and engineering principles to the protection of people, property and the environment from fire.

The Published Documents (PDs) contain guidance and information on how to undertake quantitative and detailed analysis of specific aspects of the design. They are a summary of the "state of the art" and it is intended that they be updated as new theories, calculation methods and/or data become available. They do not preclude the use of appropriate methods and data from other sources.

BS 7974 can be used to define one or more fire safety design issues to be addressed using fire safety engineering. The appropriate PDs can then be used to set specific acceptance criteria and/or undertake detailed analysis.

An alternative holistic fire safety engineering (FSE) approach can often provide a more fundamental, bespoke, safer and/or economical solution than more generic approaches to fire safety. It might, in some cases, be the only viable means of achieving a satisfactory standard of fire safety, where buildings are neither common nor straightforward.

Alternative fire safety engineering approaches can have many benefits. The use of BS 7974 is intended to facilitate the practice of fire safety engineering and in particular it:

- provides the designer with a disciplined approach to fire safety design;
- allows safety levels of specific designs to be assessed, and quantified where appropriate;
- allows the safety levels for alternative designs to be compared;
- provides a basis for selection of appropriate fire protection systems;
- provides opportunities for innovative design;
- provides information on the management of fire safety for a building.

Fire is a complex phenomenon and there are still gaps in the available knowledge. When used by suitably qualified persons experienced in fire safety engineering (see **4.2**), this series of Published Documents might provide a means of establishing adequate levels of fire safety economically without imposing unnecessary constraints on aspects of building design.

1 Scope

This Published Document provides guidance on evaluating fire growth and/or size within the enclosure of fire origin, as well as enclosures to which the fire has subsequently spread.

The characteristics and products of the design fire for any particular scenario are influenced by a number of factors, including building design, environmental influences, potential ignition sources and location, types of combustible materials, distribution and arrangement of combustible materials, ventilation conditions and other events occurring during the fire.

The determination of the characteristics and products of the design fire from ignition through to decay is used by other sub-systems.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and symbols

For the purposes of this Published Document, the following terms and definitions apply.

3.1 Terms and definitions

3.1.1 ambient condition

property of the surroundings outside the influence of a fire

3.1.2 axisymmetric plume

plume of combustion products and entrained air rising above a fire source where the air is entrained symmetrically towards the axis

3.1.3 ceiling jet

flow under a ceiling arising from the deflection of a rising plume of hot gas and smoke from a fire

3.1.4 compartment

enclosed space, which may be subdivided, separated from adjoining spaces within the building by elements of construction having a specified fire resistance

3.1.5 design fire

hypothetical fire having characteristics to serve as the basis of design

3.1.6 enclosure

volume defined by bounding surfaces, which may have one or more openings

3.1.7 equivalence ratio

fuel/air ratio divided by the fuel/air ratio required for a stoichiometric mixture

[SOURCE: BS EN ISO 13943:2017, **3.97**]

3.1.8 fire load energy

calorific energy of all of the contents within a compartment and structure that can be involved in a fire

3.1.9 fire load energy density

fire load energy per unit area

3.1.10 fire safety engineering

application of scientific and engineering principles to the protection of people, property and the environment from fire

3.1.11 heat of combustion

energy which a unit mass of material or product is capable of releasing by complete combustion

3.1.12 heat release rate

fire energy output per unit time

3.1.13 heat release rate density

heat release rate per unit area

3.1.14 sensitivity analysis

calculation of changes in outputs for variations in an input parameter of interest

3.1.15 stoichiometric oxygen demand

amount of oxygen needed by a material for complete combustion

NOTE This is the stoichiometric oxygen-to-fuel mass ratio.

3.1.16 total fire load

sum of the calorific energies, which could be released by the complete combustion and all the combustible materials in a space including the facing of the walls, partitions, floors and ceilings

3.1.17 virtual origin

theoretical point from which the plume above the flames appears to originate

3.1.18 zone model

theoretical simulation of the whole system characterizing the enclosure fire by a series of relatively few separable component processes and control volumes

NOTE Each component is represented by an equation or estimation formula.

3.2 Symbols

For the purposes of this Published Document, the following symbols and relevant units for correlations apply. The end user should verify dimensional consistency in inputs and outputs when applying the correlations presented herein.

Symbol	Unit	Description
A_{fire}	m^2	Area of the fire
A_{floor}	m^2	Total internal floor area of the enclosure
A_{max}	m^2	Maximum area of burning for a fuel-controlled fire
A_{SEA}	m^2	Smoke extinction area
A_t	m^2	Total interior surface area of the interior boundaries of the enclosure, less ventilation openings
A_v	m^2	Area of the vertical ventilation opening
α	$kW \cdot s^{-n}$	Fire growth rate parameter
C	$(m/s)^{0.5}$	Conduction factor
c_{ig}	$J \cdot kg^{-1} \cdot K^{-1}$	Specific heat capacity of the ignition material
$c_{p,0}$	$kJ \cdot kg^{-1} \cdot K^{-1}$	Specific heat capacity of ambient air
$c_{p,s}$	$kJ \cdot kg^{-1} \cdot K^{-1}$	Specific heat capacity of the enclosure boundaries
c_s	$g \cdot m^{-3}$	Smoke particulate mass concentration
d_{enc}	m	Distance front-to-back of the enclosure
D	m	Fire diameter
δ	m	Thickness
δ_s	m	Thickness of the enclosure boundaries
ε_f	–	Emissivity of the flame
ε_{smoke}	–	Proportion of smoke particulate mass yield to fuel mass loss
FTP	–	Flux-time product
g	$m \cdot s^{-2}$	Acceleration due to gravity
h_k	$kW \cdot m^{-2} \cdot K^{-1}$	Effective heat transfer coefficient of the enclosure
ΔH_c	$kJ \cdot kg^{-1}$	Total heat of combustion

Symbol	Unit	Description
$\Delta H_{c,eff}$	$kJ \cdot kg^{-1}$	Effective heat of combustion of fuel
H_v	m	Height of ventilation opening
k_{ig}	$W \cdot m^{-1} \cdot K^{-1}$	Thermal conductivity of the ignition material
k_s	$kW \cdot m^{-1} \cdot K^{-1}$	Thermal conductivity of the enclosure boundaries
K	m^{-1}	Effective emission coefficient
K_m	$m^2 \cdot g^{-1}$	Specific extinction coefficient
L	m	Length (i.e. maximum distance) of the enclosure
L_A	m	Rectangular fire source dimension (shorter side)
L_B	m	Rectangular fire source dimension (longer side)
L_f	m	Length of fire travel path
L_s	m	Smoke measurement path length
λ_f	m	Thickness of the flame
$\dot{m}''$	$kg \cdot s^{-1} \cdot m^{-2}$	Mass burning rate of fuel
m_e	kg	Equivalent fire load as wood
$\dot{m}_f$	$kg \cdot s^{-1}$	Mass loss rate of fuel
$\dot{m}_i$	$kg \cdot s^{-1}$	Mass rate of species production
$\dot{m}_{max}$	$kg \cdot s^{-1}$	Maximum mass burning rate
$\dot{m}_{part}$	$kg \cdot s^{-1}$	Mass rate of smoke particulate production
m_r	kg	Mass remaining at time t in burnt area
m_{tot}	kg	Total initial mass in burnt area
n	–	Growth power of fire
η	–	Flux-time product index
O_v	$m^{1/2}$	Opening factor
$\dot{q}''_{crit}$	$W \cdot m^{-2}$	Critical heat flux
$\dot{q}''_e$	$W \cdot m^{-2}$	Exposed heat flux
$\dot{q}''_R$	$kW \cdot m^{-2}$	Radiative heat flux
$\dot{Q}$	kW	Total heat release rate
$\dot{Q}''$	$kW \cdot m^{-2}$	Total heat release rate per unit area
$\dot{Q}^*$	–	Dimensionless heat release rate
$\dot{Q}^*_{line}$	–	Modified dimensionless heat release rate for line-shaped fire
$\dot{Q}^*_{rect}$	–	Modified dimensionless heat release rate for rectangular fire footprint
$\dot{Q}_c$	kW	Convective heat release rate
$\dot{Q}'_c$	$kW \cdot m^{-1}$	Convective heat release rate per unit length
Q''_{fd}	$kJ \cdot m^{-2}$	Fire load energy density
Q_{fd}	kJ	Fire load energy
$\dot{Q}_{fo}$	kW	Heat release rate to cause flashover temperature rise
$\dot{Q}_{max}$	kW	Maximum heat release rate
$\dot{Q}_R$	kW	Radiative heat release rate

Symbol	Unit	Description
$\dot{Q}_{steady}$	kW	Steady phase heat release rate
$\dot{Q}(t-t_{act})$	kW	Heat release rate post sprinkler activation
$\dot{Q}(t_{act})$	kW	Heat release rate at the time of activation
RTI	$(m \cdot s)^{0.5}$	Response time index of heat sensing element
r	m	Radial distance from the ceiling impingement point
ρ_0	$kg \cdot m^{-3}$	Density of ambient air
ρ_s	$kg \cdot m^{-3}$	Density of the enclosure boundaries
ρ	$kg \cdot m^{-3}$	Density of the material
s	$m \cdot s^{-1}$	Constant fire spread rate along a linear path
σ	$kW \cdot m^{-2} \cdot K^{-4}$	Stefan-Boltzmann constant (5.67×10^{-8} $kW \cdot m^{-2} \cdot K^{-4}$)
φ	–	Equivalence ratio
Δt	s	Time (change)
t	s	Time
t_{act}	s	Sprinkler activation time
t_b	s	Local burning time
t_f	s	Fire exposure time
t_i	s	Incipient phase of the fire's development
t_{ig}	s	Time to ignition
t_m	min	Time for implantation in nominal fire curves
t_{steady}	s	Duration of the steady burning phase
t_{total}	s	Total burning duration of the fire
ΔT_e	°C	Change in temperature of heat sensing element
T_0	K	Ambient air temperature
$\bar{T}_f$	K	Mean temperature of the flame
T_g	°C	Gas temperature
ΔT_g	°C	Change in gas temperature
$T_{g(max)}$	°C	Upper bound maximum post-flashover enclosure temperature
T_{ig}	K	Ignition temperature
T_s	K	Smoke temperature
θ_g	°C	Temperature rise above ambient in the upper gas layer
θ_{cj}	°C	Temperature rise in the ceiling jet
$\bar{\theta}_{cl}$	°C	Mean centreline excess gas temperature
χ_c	–	Proportion of convective heat release rate to total heat release rate
χ_R	–	Proportion of radiative heat release rate to total heat release rate
u	m/s	Velocity of gases in proximity to heat sensing element
$\bar{u}_{cl}$	$m \cdot s^{-1}$	Mean centreline gas velocity
u_{cj}	$m \cdot s^{-1}$	Gas velocity in the ceiling jet
ϕ	–	Configuration factor
$\dot{w}''$	$mm \cdot s^{-1}$	Water spray density
w_{enc}	m	Width of enclosure wall containing ventilation openings
Y_{co}	–	Proportion of CO yield mass to fuel mass loss

Symbol	Unit	Description
Y_i	–	Proportion of species yield mass to fuel mass loss
Ψ_0	–	Stoichiometric oxygen-fuel-mass ratio
z	m	Height above the fuel surface
z_0	m	Height of the virtual source above the fuel surface
z_f	m	Flame height
z_H	m	Height of the ceiling above the fire source

4 Design approach

4.1 Uncertainty

The complexity of the interactions between people, buildings and fire coupled with gaps in knowledge means that there will be a degree of uncertainty associated with any fire safety design. Uncertainties can exist in underlying science and research, theoretical models, experiments and tests, design, systems and component performance and reliability, and construction and operational quality.

Part of the designer's role is to identify uncertainties and adequately mitigate any associated risk to as low as reasonably practicable (ALARP). It is likely that the greater the risk, the more significant the mitigation required. Mitigation can include increased conservatism, redundancy, robustness and/or reliability. Assessing the adequacy of mitigation is likely to involve sensitivity analysis. The objective of a sensitivity analysis is to establish the impact on the output parameter(s) caused by variation in the input parameter(s); it is not intended to check the accuracy of the results.

All relevant uncertainty should be identified, documented and adequately addressed. This should include documenting any limitations on the building in order to communicate residual risks and areas requiring additional monitoring and/or risk mitigating measures.

Where it is intended to specifically quantify the level of safety achieved by a design, the probabilistic risk assessment (PRA) methods set out in PD 7974-7 should be used. The tools in this document may be applied in a probabilistic manner through the identification of appropriate stochastic input values for relevant variables.

4.2 Competence

The application of FSE should be entrusted to suitably qualified and experienced people at all stages. BS 7974:2019, **4.1**, discusses competence in the context of fire safety engineering.

4.3 Framework

A framework of the application of engineering approaches to fire safety in buildings is provided in BS 7974.

The basis of any assessment or sub-assessment can be empirical or theoretical, the accuracy can be approximate or realistic, the analysis can be deterministic or risk-based and the measure can be qualitative or quantitative. Regardless of what combination is adopted, the design assessment, basis of design fire selection, etc., should be consistent and compatible.

The quantitative analysis necessary as part of the design is divided into a number of separate parts or sub-systems. Each sub-system can be used in isolation when analysing a particular aspect of design or they can all be used in combination as part of an overall alternative fire engineering evaluation of a building.

Sub-system 1 concentrates on the quantification judgements that can form the part of the design process in which the initiation and development of the fire are defined. The calculation methods and data contained in this sub-system are included with the known limitations. Alternative calculation methods are not precluded and might be required. Satisfactory justification of any calculation method, adopted data or approach selected should always be provided.

4.4 Design assessment and basis of design fire selection

As part of the design process, it is necessary to assess the adequacy of the trial fire safety design in achieving the fire safety goals. Often, this involves selecting one or likely multiple separate design fires against which the performance of the design can be tested. To be valid, design fires should be:

a) consistent with the fire safety goals. For example, equivalency to a fire resistance rating in accordance with BS 476-20 requires the adoption of the ISO 834 standard fire curve;

b) compatible and/or conservative in the context in which they are being used. For example, for a 'realistic' assessment, design fires should either be compatible with the expected fire dynamics or conservative relative to the expected fire dynamics;

c) sufficiently onerous to mitigate any uncertainty and/or to adequately test the trial fire safety design with the fire safety goals.

Additional information on design fires can be found in BS ISO 16733-1.

4.5 Building characteristics

Information on building characteristics will be provided from the qualitative design review (QDR) and consideration in terms of the potential consequences should be given to factors influencing the fire growth, spread and extinguishment process which, for example, include:

a) building:
   1) dimensions of construction/building;
   2) geometry of construction/building;
   3) nature of construction of building (materials and methods).
b) enclosure:
   1) wall and ceiling linings;
   2) ventilation conditions (micro, macro, natural and mechanical);
   3) fuel load;
   4) potential ignition sources.
c) active measures (if not included as part of the trial fire safety design);
   1) active fire barriers;
   2) smoke ventilation;
   3) suppression;
   4) manual firefighting.

The building characteristics might be dynamic and change in accordance with events during the fire scenario, for example, doors opening or closing, active systems activating, windows breaking, openings occurring in enclosures, etc.

4.6 Fuel load characteristics

Information on fuel load will be provided from the QDR and consideration in terms of the potential consequences should be given to the contributions from all relevant factors influencing the fire growth and spread process, which include:

a) type of combustibles;

b) quantity of combustibles;

c) location of combustibles;

d) arrangement of combustibles.

The fuel load characteristics might be dynamic and change in accordance with events during the fire scenario, for example, pyrolysis, delamination of materials and composites, liquefaction of combustibles, fluid fuels flowing, etc.

4.7 Environmental influences

Information on environmental influences will be provided from the QDR and consideration should be given to how environmental conditions (which might be dynamic) can influence fire growth, spread and the extinguishment process, mass and heat transfer, and enclosure pressure. These might include:

a) internal and external temperatures;

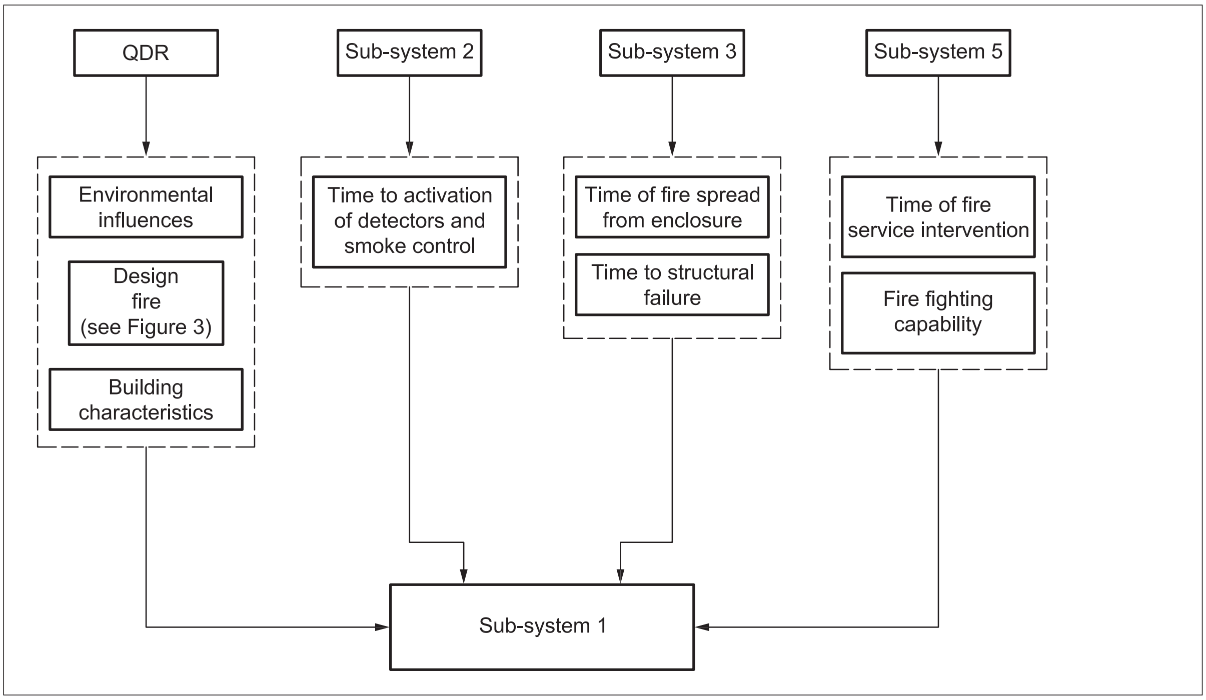
b) internal and external air movement;

c) internal and external oxygen concentrations.

5 Inputs

The inputs given in Sub-system 1 are illustrated in Figure 1.

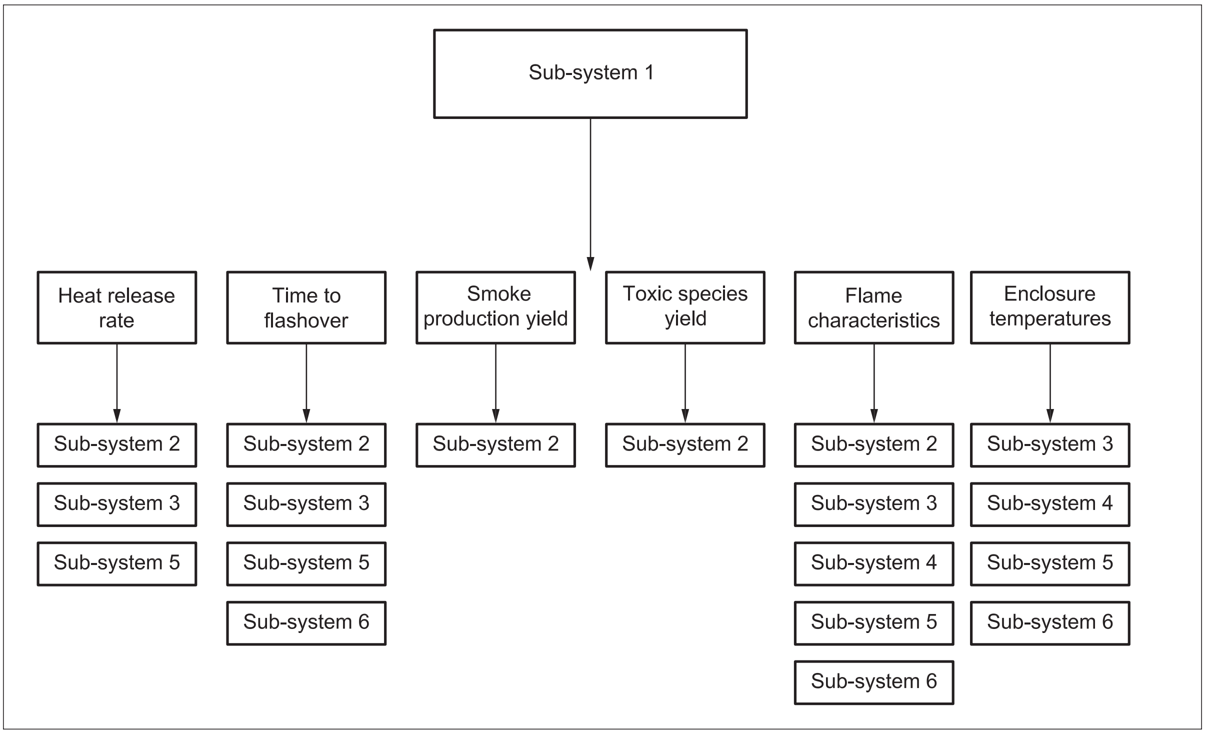
Figure 1 — *Sub-system 1 inputs*



6 Outputs

The outputs given in Sub-system 1 are illustrated in Figure 2.

Figure 2 — *Sub-system 1 outputs*



7 Classification

7.1 General

The time evolution of a fire can be described according to the following stages:

a) ignition;

b) flame spread;

c) growth;

d) fully developed fire: localized, flashover or travelling;

e) decay; and

f) end stage: burnout, self-extinction, or suppression.

The stages of fire development noted are not necessarily in chronological order. The transition between stages can be impacted by, for example, sudden changes in ventilation conditions, the exposure of new fuel (e.g. due to the delamination of timber linings, failure of plasterboard, etc.), or spread into enclosures, where fires can undergo transition to flashover.

7.2 Ignition

Ignition is the process by which a fire in an enclosure starts. It can lead to smouldering or flaming fires, but the emphasis in this document is on flaming fires because they are generally quicker to grow, more powerful in terms of energy released and generate more smoke. Smouldering fires can undergo transition into flaming fires.

Ignition can be piloted, which requires the presence of a pilot flame, spark or hotspot. Alternatively, ignition can be spontaneous (also sometimes called auto-ignition), or as the result of self-heating. Generally, piloted ignition requires smaller ignition sources to be initiated compared with spontaneous ignition.

Potential sources of ignition include a smouldering source, naked flame, hot surface or hotspot, electric discharge, heaters, hot works, cookers, engines and boilers, lighting equipment, friction between surfaces and chemically reactive material.

Consideration should be given to the most probable ignition source, location and fuel likely to be first ignited. Secondary ignition of additional fuel items is part of fire growth.

7.3 Flame spread

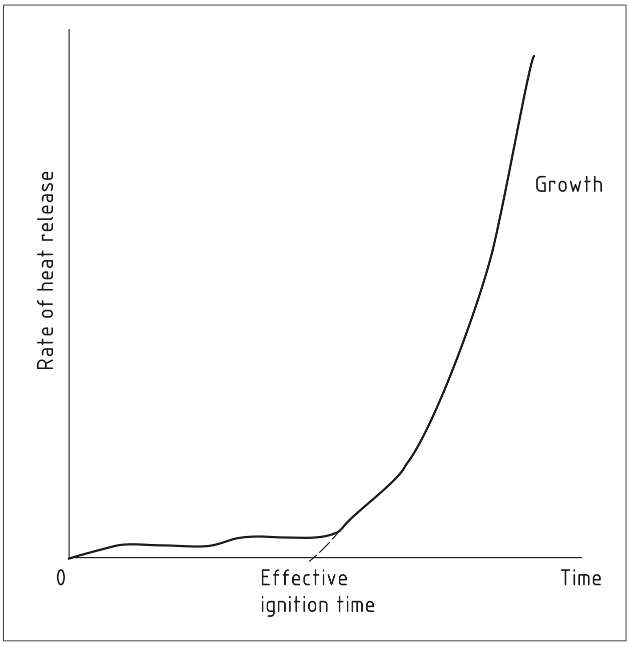
Flame spread is the means by which a fire spreads progressively over a fuel surface. The surface can be oriented horizontally, vertically or at some intermediate alignment. The flame spread can be over multiple surfaces within the same fuel item, e.g. wood pallets.

During flame spread, there is heat transfer from the flames to the fuel item which causes pyrolysis ahead of the spread. The pyrolysis gases burn in the flame, the heat from which in turn produces more pyrolysis. The spread of flame can be aided by natural buoyancy or external air flow, e.g. wind or HVAC system.

7.4 Fire growth

The growth stage of the fire is characterized by an increasing rate of heat release as flame spreads over burning fuel items or ignites other fuel items located in the vicinity (secondary ignition). The rate of growth is a function of several variables but the most important ones are the fuel type, geometry, ignition properties, and orientation of fuel surfaces. Growth can be either by smouldering or flaming, but flaming growth is much quicker. Fire growth during the pre-flashover stage is illustrated in Figure 3.

Figure 3 — *Conceptual illustration of continuous fire growth*



7.5 Fully developed

7.5.1 General

Fully developed is the stage where a fire has developed to its full potential given its enclosure(s). The fire has reached its maximum potential heat release rate, assuming there are no external fire suppression influences. This stage can be generally characterized by the three scenarios described in **7.5.2** to **7.5.4**.

7.5.2 Localized fire

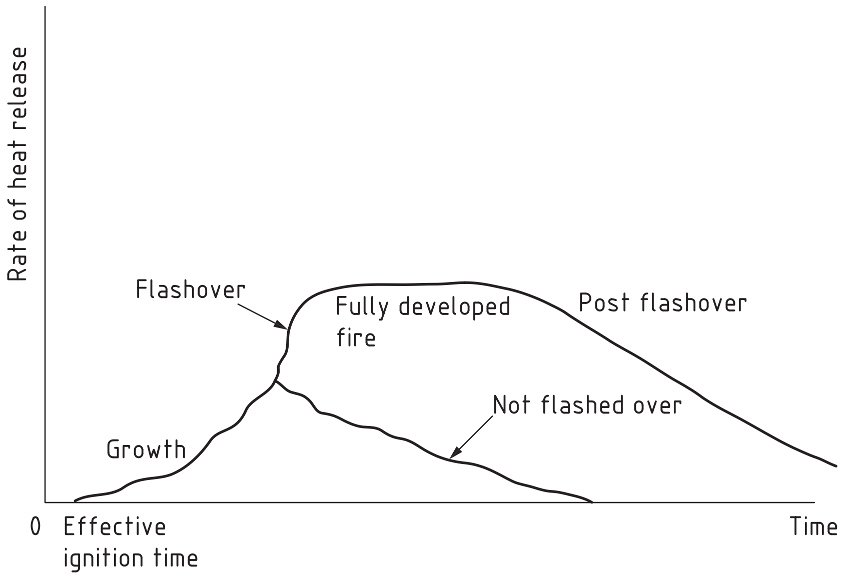
When the fire only burns a small-size fuel item relative to the size of the enclosure it might remain localized because no other fuel items are present or because no other fuel items are sufficiently close for secondary ignition.

The fire then produces two regions inside the enclosure: the near field is in the vicinity of the flames (a smaller region where the highest temperatures are located), and the far field is created by the smoke (the larger region where lower temperatures are located).

7.5.3 Flashover

Flashover is the sudden transition from gradual fire growth to the involvement of all fuel items that have yet to ignite in the enclosure which then start to burn near simultaneously. Flashover is illustrated in Figure 4.

Figure 4 — *Fire growth in an uncontrolled room fire*



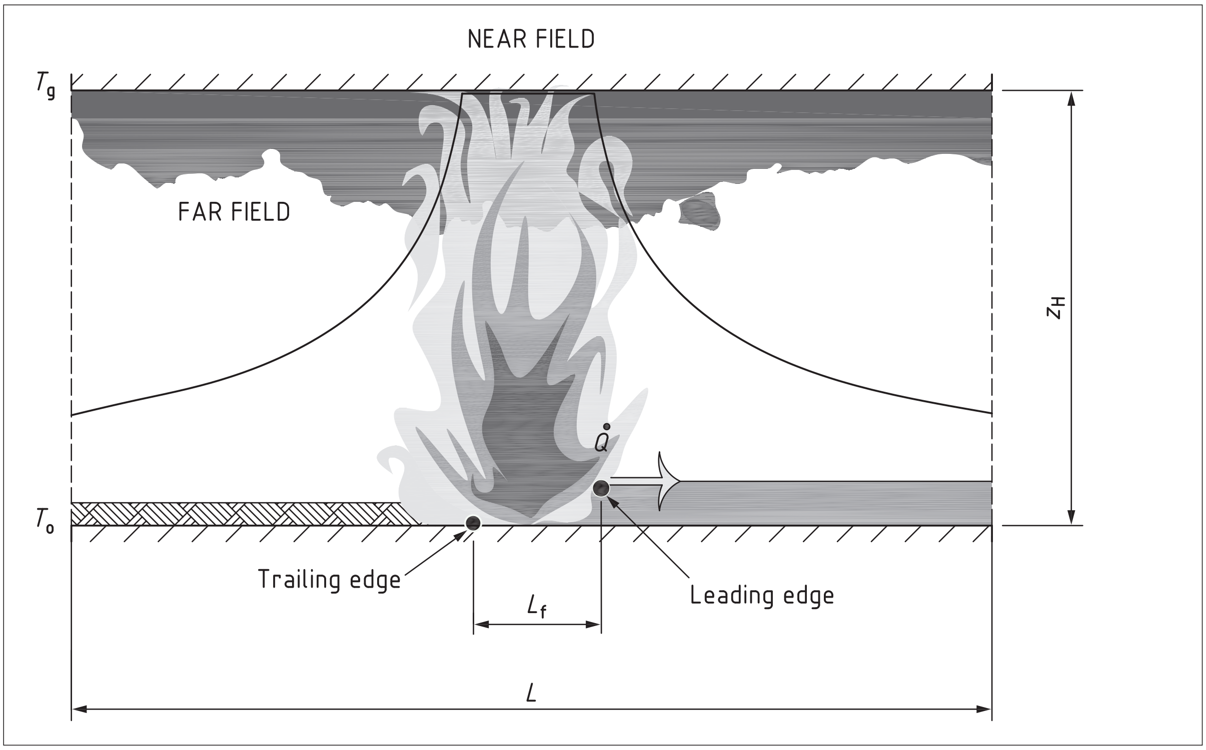
For a ventilation-controlled regime, the available ventilation imposes an upper limit on the energy release. During the course of the fire there might be an increase in ventilation. This could be due to windows breaking, fire service intervention or the operation of air handling or smoke extract systems.

For a fuel-controlled regime, combustibles are able to burn freely and the rate of heat release is limited by the amount, type and surface of the burning items.

7.5.4 Travelling fire

A travelling fire burns over a limited area of fuel but moves through the enclosure as flames spread over time from one fuel item to another. A travelling fire occurs inside enclosures which are typically large or not ventilation constrained. The size of the fire is dictated by the fuel area burning between the leading edge of the flames (where flame spread occurs) and the trailing edge of the flames (where burnout takes place). A travelling fire can be generally conceptualized as a localized fire that moves. As such, a travelling fire produces two regions inside the enclosure, the near field and the far field. See Figure 5.

Figure 5 — *Illustration of a travelling fire and ceiling jet [1]*



7.6 Decay

The decay stage of a fire is when it is running out of fuel and there is less of it left to burn than during the fully developed stage. The rate of heat release of the fire and the average temperature within the enclosure typically undergo a continuous decrease over time.

7.7 End stage

7.7.1 Burnout

Burnout is a possible end point to a fire after the decay stage caused by the fuel in the enclosure being completely consumed.

7.7.2 Self-extinction

Self-extinction is a possible end point to a fire while fuel is still available in the enclosure. This extinguishment mechanism occurs because remaining fuel items cannot support continued burning, or there is a lack of oxygen, or the heat transfer from the fire and the enclosure is insufficient to cause secondary ignition of remaining fuel items. It could occur at the growth, fully developed or decay stages.

7.7.3 Suppression/intervention

The intervention of people (e.g. the fire service) or of an automatic system can affect the growth of a fire, reduce the rate of heat release to some lower value or initiate a period of decay that can also result in eventual extinction of the fire. Intervention can affect the fire during its growth phase or once a fire has reached its fully developed phase.

8 Design calculations

8.1 General concepts/principles

8.1.1 Heat release rate

The total amount of heat (energy) released by a fire per unit of time depends on its heat of combustion and the mass of fuel burned per unit time such that:

$$\dot{Q} = \dot{m}_{\mathrm{f}} \Delta H_{\mathrm{c,eff}} \tag{1}$$

NOTE 1 Limits. This equation assumes complete combustion of the vaporized fuel. In vitiated conditions, there is significant incomplete combustion, particularly for ceiling fires and caution should be used when applying this formula to calculate heat release rates.

NOTE 2 Due to a limited availability of fuel or oxygen, the heat release rate will converge on a maximum (see 8.5.2).

8.1.2 Radiative and convective heat release rate

The convective heat output is given by:

$$\dot{Q}_{\mathrm{C}} = \chi_{\mathrm{c}} \dot{Q} \tag{2}$$

Correspondingly, the radiative heat output is:

$$\dot{Q}_{\mathrm{R}} = \left(1 - \chi_{\mathrm{c}}\right) \dot{Q} \tag{3}$$

where the convective fraction χ_{c} can range from 0.4 to 0.9 depending upon the fuel. Data for particular fuels can be found in the SFPE Handbook of Fire Engineering [2], with some indicative values given in Annex A. However, for many typical applications, a value of $\chi_{\mathrm{c}} \approx 0.7$ is appropriate.

8.1.3 Heat release rate density

The fire heat release rate can be estimated from the heat release rate per unit area, and the area of burning using:

$$\dot{Q} = \dot{Q}'' A_{\mathrm{fire}} \tag{4}$$

8.1.4 Dimensionless heat release rate

Dimensionless heat release rate for a circular fire source is:

$$\dot{Q}^{*} = \frac{\dot{Q}}{\rho_0 c_{\mathrm{p},0} T_0 g^{1/2} D^{5/2}} \tag{5}$$

8.2 Ignition

8.2.1 Steady state

The ignition of fuels depends on a number of factors including the physical state of the fuel (gas, liquid or solid), the heating mechanisms (via radiation, convection and/or conduction), the presence of a separate pilot source such as a spark or ember and whether the ignition is flaming, spontaneous or smouldering. For more detail regarding the topic see the Ignition Handbook by Babrauskas [3] or the relevant chapters in the SFPE Handbook of Fire Protection Engineering [2].

In many applications the time to ignition of solid materials is of particular interest. Formulae (6) to (8) are for the piloted ignition of solid materials exposed to a constant heat flux according to Mikkola and Wichman [4]. The time to ignition depends on the thermal thickness of the material which relates to the heat losses from the sample surface. A material that is 2 mm thick or less can be assumed to be thermally thin, a material thicker than 1.5 cm can be treated as being thermally thick and thickness in-between these two limits taken to be thermally intermediate.

For a thermally thick material the time to ignition can be found using:

$$t_{ig} \approx k_{ig} \rho c_{ig} \left(\frac{T_{ig} - T_0}{\dot{q}''_e - \dot{q}''_{crit}} \right)^2 \qquad (6)$$

The time to ignition of a thermally thin material can be found using:

$$t_{ig} \approx \rho c_{ig} \delta \left(\frac{T_{ig} - T_0}{\dot{q}''_e - \dot{q}''_{crit}} \right) \qquad (7)$$

and the time to ignition of a thermally intermediate material can be found using:

$$t_{ig} \approx \rho c_{ig} \sqrt{k_{ig} \delta} \left(\frac{T_{ig} - T_0}{\dot{q}''_e - \dot{q}''_{crit}} \right)^{3/2} \qquad (8)$$

Values for k_{ig} and c_{ig} are apparent thermal properties obtained from relevant ignition experiments. Similarly, $\dot{q}''_{crit}$ needs to be obtained from experimental data or references for the given material.

8.2.2 Transient

The flux-time product (FTP) method, initially proposed by Smith and Satija [5] and subsequently modified by Shields, Silcock, Murray [6] and Toal [7], can be used to determine the piloted ignition of materials exposed to time varying incident heat fluxes. The FTP is calculated in a piece-wise fashion (i = 1, 2, ... m) such that:

$$FTP = \sum_{i=1}^{m} \left(\dot{q}''_e - \dot{q}''_{crit} \right)^{\eta} \cdot \Delta t \qquad (9)$$

and the exposure heat flux $\dot{q}''_e$ exceeds the critical heat flux $\dot{q}''_{crit}$ of the material. When the cumulative FTP exceeds the target FTP value for the material then ignition occurs. The η index corresponds to the thermal thickness such that η = 2 for thermally thick materials, η = 1 for the thermally thin case and η = 3/2 for the thermally intermediate situation when following the method of Mikkola and Wichman [4]. However, the work by Shields and co-workers [6] suggests that η could assume any value in the range between 1 and 2 depending on the specific conditions.

NOTE The limits for the three thermal conditions are not precisely defined in Mikkola and Wichman [4] such that the limits given here are an interpretation of values quoted from their analysis.

8.3 Characteristics of flames

8.3.1 Virtual origin

For normal atmospheric conditions and fire sources which do not have substantial in-depth combustion, i.e. where ~2/3 or greater of the volatiles released undergoes combustion above the fuel array, an estimation of a fire's virtual origin can be obtained using [8]:

$$z_0 = -1.02D + 0.083\dot{Q}^{2/5} \qquad (10)$$

8.3.2 Mean flame heights

8.3.2.1 Square and circular fire sources

Flame heights for diffusion flames can be described as a function of Froude number or some of its variations (non-dimensional heat release rate, in this case). Table 1 gives three of the more common empirical correlations (normalized relative to fire diameter), with information regarding the experiments underpinning the correlations, and the $\dot{Q}^*$ range over which the correlations have been observed as valid.

Table 1 — *Empirical correlations*

Reference	$\dot{Q}^*$ Range A)	Z_f/D	Other comments
Zukoski [9]	$\dot{Q}^* < 0.15$	$40\dot{Q}^{*2}$	Natural gas: 10 cm to 50 cm diameter burner
	$0.15 < \dot{Q}^* < 1.0$	$3.3\dot{Q}^{*\frac{2}{3}}$	
	$1 < \dot{Q}^* < 40$	$3.3\dot{Q}^{*\frac{2}{5}}$	
Thomas [10]	$0.75 < \dot{Q}^* < 8.8$	$3.4\dot{Q}^{*0.61}$	10 cm to 200 cm side wood cribs ΔH_c = 18.6 MJ/kg
Heskestad [11]	$0.12 < \dot{Q}^* < 12{,}000$	$3.7\dot{Q}^{*\frac{2}{5}} - 1.02$	Gas, liquids and solids $\Delta H_c / \varphi^2$ = 3 185 kJ/kg of air

A) Represent the ranges presented by the originators. Further research might have been conducted that extends the valid range of application.

Where fire diameters are large, i.e. at a Froude number corresponding with $\dot{Q}^*$ ″ 0.01 ≤ 0.01, continuous flame cover over the fuel bed does not occur. Instead, discrete flames of reduced height (relative to the diameter) are observed [12].

8.3.2.2 Rectangular and line fire sources

The correlations noted in **8.3.2.1** may be adopted with a modified $\dot{Q}^*$ for rectangular and line sources.

For a rectangular source of dimensions $L_A \times L_B$ (shorter and longer sides, respectively) $\dot{Q}^*$ should be modified per Formula (11):

$$\dot{Q}^*_{\text{rect}} = \frac{\dot{Q}}{\rho_0 c_{p,0} T_0 \sqrt{g} L_A^{1.5} L_B} \tag{11}$$

For a line source, L_B is set to unity, leading to Formula (12):

$$\dot{Q}^*_{\text{line}} = \frac{\dot{Q}_l}{\rho_0 c_{p,0} T_0 \sqrt{g} L_A^{1.5}} \tag{12}$$

Flame height is directly related to mass entrainment. Grove and Quintiere [13] indicate that line source flame heights will generally be conservatively estimated based upon axisymmetric correlations (i.e. **8.3.2.1**) where the aspect ratio of the source is not less than $L_A / L_B = 0.4$. Data was taken from a variety of sources. Fuels include methanol, propane, methane, acetone, hydrogen and wood and produce fires ranging from 2.79 kW·m^{-1} to 342 kW·m^{-1}.

For the subsequent calculation of flame height from a rectangular or line source, formula (13) is given by Yuan and Cox [14]:

$$\frac{Z_{\mathrm{f}}}{L_{\mathrm{A}}} = 3.46\dot{Q}^{*}_{\mathrm{rect/line}} \tag{13}$$

Formula (13) holds for $\dot{Q}_{\mathrm{l}}$ > 30 kW/m.

8.3.3 Plume temperature and velocity

The mean centreline (or axial) excess gas temperature and mean centreline gas velocity for an axisymmetric plume can be given by Formulae (14) and (15) [8]:

$$\bar{\theta}_{\mathrm{cl}} = 9.1\left(\frac{T_0}{g c_{\mathrm{p,0}}^2 \rho_0^2}\right)^{1/3} \dot{Q}_{\mathrm{c}}^{2/3}\left(z - z_0\right)^{-5/3} \tag{14}$$

$$\bar{u}_{\mathrm{cl}} = 3.4\left(\frac{g}{c_{\mathrm{p,0}} \rho_0 T_0}\right)^{1/3} \dot{Q}_{\mathrm{c}}^{1/3}\left(z - z_0\right)^{-1/3} \tag{15}$$

For atmospheric conditions where T_0 = 293 K, g = 9.81 m·s^{-1}, $c_{\mathrm{p,0}}$ = 1.0 kJ·kg^{-1}·K^{-1} and ρ_0 = 1.2 kg·m^{-3} Formulae (14) and (15) reduce to:

$$\bar{\theta}_{\mathrm{cl}} = 25\dot{Q}_{\mathrm{c}}^{2/3}\left(z - z_0\right)^{-5/3} \tag{16}$$

$$\bar{u}_{\mathrm{cl}} = 1.03\dot{Q}_{\mathrm{c}}^{1/3}\left(z - z_0\right)^{-1/3} \tag{17}$$

Formulae (16) and (17) cease to be valid near the mean flame height and below for fire sources without substantial in-depth combustion, i.e. where:

$$\left(z - z_0\right) / \dot{Q}_{\mathrm{c}}^{2/5} < 0.15\ \mathrm{m{\cdot}kW^{-2/5}}\ \text{to}\ 0.20\ \mathrm{m{\cdot}kW^{-2/5}} \tag{18}$$

Below this limit, experiments indicate a convergence on a temperature rise deep in the flame of c. 900 K. Fires with very low flame heights (Z_{f}/D) can generally be expected to produce lower maximum mean temperatures. Atypical fuel types can also produce higher maximum mean temperatures.

8.3.4 Heat flux from flames

The radiant heat flux from a flame depends on a number of factors and is represented via the common Boltzmann equation:

$$\dot{q}''_{\mathrm{R}} = \phi \varepsilon_{\mathrm{f}} \sigma \bar{T}_{\mathrm{f}}^4 \tag{19}$$

The configuration factor ϕ enables the calculation of radiant intensity at a point remote from the radiator. For the purposes of calculating ϕ, the flame is typically approximated to be a simple geometric shape such as a rectangle, cylinder or cone. If the flame is influenced by external air flows or fire induced flows, the appropriate configuration factor can be found in McGuire [15], Drysdale [12] or the SFPE Handbook [2]. Common configuration factors are given in Annex C.

For a luminous flame, the emissivity may be taken as:

$$\varepsilon_\mathrm{f} = 1 - \exp\left(-K\lambda_\mathrm{f}\right) \tag{20}$$

This simple method for calculating emissivity should not be used for large fires as it assumes that temperature and soot concentration are uniform [12]. Therefore, if the flame thickness $\lambda_\mathrm{f} > 1$ m and the flame is luminous, it is common to assume black body behaviour and that the emissivity of the flame $\varepsilon_\mathrm{f} = 1$.

Calculation of radiative heat fluxes from flames requires as input data flame emissivity, effective values of flame temperature and that the flame be idealized as a simple geometric shape, such as a rectangle, cylinder or cone. A simpler model, based upon radiation propagating from a point source has been shown to be reliable in many cases [16], i.e.:

$$\dot{q}''_\mathrm{R} = \frac{\chi_\mathrm{R}\dot{Q}}{4\pi d^2} \tag{21}$$

with *d* the distance from the point source to the receiver (m) and χ_R the proportion of the total heat release rate that is radiative, i.e. $1 - \chi_\mathrm{c}$.

The model has been shown to be accurate where $d/D > 2.5$, and presumes that the receiver is perpendicular to line of sight originating from the point source, yielding a maximum $\dot{q}''_\mathrm{R}$.

8.4 Fire growth

8.4.1 Characteristic fire growth curve — alpha t^n

The growth phase of a fire can be characterized according to the generalized relationship below:

$$\dot{Q} = \alpha\left(t - t_\mathrm{i}\right)^n \tag{22}$$

The constants α and n are readily derived from experiments, e.g. data is available via Mayfield and Hopkin [17]. The correlation is only valid prior to the fire becoming fully developed. Table 2 provides general constants for standardized growth rates.

Table 2 — *Standardized alpha t-squared growth rates*

Growth rate	Time to reach 1 055 kW s	α kW·s^{-2}	*n*
Slow	600	0.0029	2
Medium	300	0.0117	
Fast	150	0.0469	
Ultra-fast	75	0.1876	

Differing fuel configurations can be better idealized using a different power, e.g. fires involving racked goods may exhibit growth behaviour better characterized by $n > 2$. It should be noted that *n* need not be an integer. Annex A contains sample data for a limited range of items.

8.4.2 Enclosure temperatures

There are several approximate methods to predict the temperature of the hot upper layer in an enclosure fire prior to flashover and where upper layer temperatures can be expected to be relatively uniform. Such methods do not predict the local temperatures, which might be used to determine when a detector or sprinkler will be triggered. The relationship shown in Formula (23) was originally derived from experimental data, by McCaffrey, Quintiere, Harkleroad [18] and then extended by work from Mowrer and Williamson [19], Karlsson [20], Azhakesan et al. [21] and Azhakesan and Quintiere [22]. This method uses a zone model concept and assumes a uniform hot gas layer that collects under the ceiling. It can be used to calculate the temperature rise above ambient in the enclosure provided that the upper gas layer does not exceed between 500 °C to 600 °C, based on the assumption that flashover can occur in this range:

$$\theta_{\mathrm{g}} = C_{\mathrm{T}} \left(\frac{\dot{Q}^2}{A_{\mathrm{v}} H_{\mathrm{v}}^{1/2} h_{\mathrm{k}} A_{\mathrm{t}}} \right)^{1/3} \qquad (23)$$

Formula (23) can be used for enclosures with several wall openings by summing the $A_{\mathrm{v}} H_{\mathrm{v}}^{1/2}$ values for each vent.

NOTE 1 The enclosures assessed in [6] were between 0.3 m to 2.7 m high by 0.14 m² to 12 m² floor area.

C_T is an empirical constant that can be used for different fire configurations, see Table 3. Recommended values are given below based on the original research studies, as summarized in [23]:

Table 3 — *C_T constants for different configurations*

Configuration	C_T
Discrete, centred	6.85
Discrete, against wall	8.78
Discrete, corner	12.22
Linings, walls only	17.14
Linings, wall and ceiling	14.28

For the case where the thermal penetration time for the enclosure boundaries is greater than the fire exposure time, i.e. heat transfer is transient or non-steady:

$$h_{\mathrm{k}} = \left(\frac{k_{\mathrm{s}} \rho_{\mathrm{s}} c_{\mathrm{p,s}}}{t_{\mathrm{f}}} \right)^{1/2} \qquad (24)$$

or for the case where the thermal penetration time for the enclosure is significantly shorter than the fire exposure time, i.e. heat transfer is steady:

$$h_{\mathrm{k}} = \frac{k_{\mathrm{s}}}{\delta_{\mathrm{s}}} \qquad (25)$$

McCaffrey, Quintiere, Harkleroad [18] provide further discussion on the estimation of thermal penetration time.

Formula (23) can be used for enclosures using a mixture of different boundary construction materials by summing the h_{k} and individual areas of the various wall, ceiling and floor elements.

For a conservative design approach with respect to maximum temperature rise, the steady state condition can be considered, i.e. Formula (25). The non-steady condition can be evaluated by adopting the greater of Formulae (24) and (25).

NOTE 2 Limits. Care has to be taken:

a) when the fire enclosure has more than one opening;

b) for a very well-insulated fire enclosure or in other situations when $h_{\mathrm{k}} \rightarrow 0$;

c) for complicated fire enclosure geometries;

d) in large enclosures in which significant fire growth has occurred before the combustion products have exited the enclosure.

8.4.3 Ceiling jets

8.4.3.1 General

When a fire plume impinges on a ceiling, the flow of gases turns to move horizontally beneath the ceiling and then to spread to other areas of the building. The velocity and temperature of these gases typically need to be known to enable detector and sprinkler activation times to be assessed since this is where such devices are usually installed. Under horizontal ceilings the gases initially move away from the impingement point in an axisymmetric ceiling jet until they impinge bounding walls, beams etc. The depth of ceiling jets is typically between 5% to 12% of the height of source-to-ceiling fire plume. The maximum gas velocities and temperatures occur within this jet at approximately 1% of the total fire source-to-ceiling height, below the ceiling. In the particular circumstances of narrow channels, such as corridors or under beamed ceilings, a new two-dimensional ceiling jet becomes established.

The properties of the ceiling jet are dependent upon the surface roughness of the ceiling together with heat losses to it. Most of the methods available in [24] calculate the maximum temperature and velocity in the ceiling jet. If detectors or sprinkler heads are situated substantially lower than where the maximum temperature and velocity occur, then longer activation times should be expected.

For time-dependent design fires, the Formulae (26) and (27) can be assumed to be quasi-steady and the time-varying rate of heat release inserted into the appropriate formula. As an alternative, computational fire models can be of particular assistance with these calculations.

8.4.3.2 Axisymmetric ceiling jet

The maximum temperatures and velocities in an unconfined axisymmetric ceiling jet under a smooth horizontal ceiling produced by a steady fire are [2]:

$$\theta_{\text{cj}} = 6.721 \frac{\dot{Q}_{\text{c}}^{2/3}}{\left(z_{\text{H}} - z_0\right)^{5/3}} \left(\frac{r}{z_{\text{H}} - z_0}\right)^{-0.6545} \quad \text{for} \quad \frac{r}{z_{\text{H}} - z_0} > 0.134 \tag{26}$$

and

$$u_{\text{cj}} = 0.2526 \frac{\dot{Q}_{\text{c}}^{(1/3)}}{\left(z_{\text{H}} - z_0\right)^{1/3}} \left(\frac{r}{z_{\text{H}} - z_0}\right)^{-1.0739} \quad \text{for} \quad \frac{r}{z_{\text{H}} - z_0} > 0.246 \tag{27}$$

NOTE The ceiling jet formulae assume that the jet is moving through ambient air and is not submerged within a ceiling smoke layer. Existing correlations in 8.3.3 for the maximum temperature and velocity in the plume can be used when $\frac{r}{Z_{\text{H}} - Z_0}$ *are less than or equal to the limits given.*

8.5 Fully-developed fires (inclusive of decay)

8.5.1 Transition to flashover

8.5.1.1 Conditions for flashover

For enclosures without combustible linings, flashover can be assumed to occur when sustained flaming from fuel items reaches the ceiling and the average temperature of the hot gas layer is between 500 °C and 600 °C. These conditions are generally sufficient to increase the likelihood of piloted ignition and enhance flame spread over the surface of combustible items that are not yet burning in an enclosure. If flames from the combustibles do not reach the ceiling, or the average gas layer temperature remains below 500 °C, flashover can be assumed to be unlikely.

8.5.1.2 Heat release rate (HRR) at flashover

After flashover, the rate of heat release will increase rapidly until it reaches the maximum value. To simplify design, the growth period between the onset of flashover and the maximum heat release rate is usually ignored, and it can be assumed that when flashover occurs the rate of heat release instantaneously increases to the maximum value. This assumption is conservative in relation to its estimation of the time to reach the maximum heat release rate.

Two methods of calculation can be used:

a) Method 1

Thomas [25] developed an analysis basing the heat flow through an opening on a mass inflow expressed in terms of ventilation control. The rate of heat release required for flashover to occur, which is based upon the assumption that flashover occurs at an upper layer temperature rise of 600 °C, is:

$$\dot{Q}_{\mathrm{fo}} = 7.8 A_{\mathrm{t}} + 378 A_{\mathrm{v}} H_{\mathrm{v}}^{1/2} \tag{28}$$

b) Method 2

By choosing a temperature rise of 500 °C as the flashover temperature and substituting this into Formula (23), McCaffrey et al. [18] derived the expression for the necessary heat release rate to cause this temperature rise for discrete fires away from the walls of an enclosure. This formula differs from Method 1 [Formula (28)] in that it includes explicitly heat transfer through the enclosure boundaries.

$$\dot{Q}_{\mathrm{fo}} = 610 \left(h_{\mathrm{k}} A_{\mathrm{t}} A_{\mathrm{v}} H_{\mathrm{v}}^{1/2} \right)^{1/2} \tag{29}$$

NOTE 1 Limits. McCaffrey et al. [18] stated that they had not included "extensive data" from ventilation-controlled fires, and that all data were for fires near the centre of an enclosure. They do not give any data on the fire perimeters.

NOTE 2 The enclosures were in the range of 0.3 m to 2.7 m high by 0.14 m² to 12 m² floor area. Almost all the openings were taller than they were wide, and that some were very narrow indeed. It is, therefore, significant that McCaffrey et al. [18] included a caution that their correlation might be less relevant for "very different" experiments.

NOTE 3 Limits. Formulae (28) and (29) are only valid when a two-directional flow has been established in the vertical ventilation opening(s) i.e. the formulae are not applicable to the smoke-filling phase of an enclosure fire process. The models assume a hot gas layer of uniform temperature. They are not applicable to fire process controlled by ventilation. Care has to be taken:

a) when the fire enclosure has more than one opening;

b) for a very well-insulated fire enclosure or in other situations when $h_k \rightarrow 0$;

c) when fire growth is extraordinarily fast;

d) for fires in corners or adjacent to a wall;

e) for complicated fire enclosure geometries.

In addition, the models are based on experiments with wall material of relatively high thermal inertia and can be less conservative for highly insulated fire enclosures.

Caution should be used with these formulae and they should only be used where an enclosure is similar to those used in the experiments.

8.5.2 Maximum HRR

8.5.2.1 General

The maximum heat release rate is given by:

$$\dot{Q}_{\max} = \dot{m}_{\max} \Delta H_{\mathrm{c,eff}} \quad (30)$$

The maximum mass burning rate can either be as a result of the available flow of air (oxygen) into an enclosure or, where an excess of oxygen is available, due to the maximum amount of fuel that can burn at a given point in time.

8.5.2.2 Ventilation controlled

In a ventilation-controlled fire the heat release is limited by the oxygen that can reach the fuel to sustain burning. Following the work of Kawagoe [26] the ventilation-controlled mass burning rate can be found using:

$$\dot{m}_{\max} = 0.09 A_{\mathrm{v}} H_{\mathrm{v}}^{1/2} \quad (31)$$

which is valid for:

$$\frac{\rho_0 \sqrt{g} A_{\mathrm{v}} \sqrt{H}}{A_{\mathrm{floor}}} < 0.24 \quad (32)$$

The ventilation-controlled rate of heat release can be calculated using:

$$\dot{Q}_{\max} = 1500 A_{\mathrm{v}} H_{\mathrm{v}}^{1/2} \quad (33)$$

NOTE This formula makes a number of assumptions regarding the heat of combustion of the fuel, the location of the neutral plane in a compartment fire, etc.

During the course of the fire there might be a change in ventilation. This could be due to windows breaking, fire service intervention or the operation of the air handling or smoke extractor systems. For design purposes, it might be necessary to estimate the time at which such changes can occur and the influence they might have on the fire. One possible approach to this is to assume a characteristic fire profile and then include events such as window breakage by calculating the effect of the change in ventilation on the profile. Excess fuel volatiles that are unable to burn within the space can burn when they encounter additional oxygen, one example of which is external flaming from a building.

8.5.2.3 Fuel controlled

In a fuel-controlled fire the maximum heat release rate is set by the mass of fuel that is able to burn at a point in time. Often the mass burning rate is dictated by the exposed area of the fuel surfaces where:

$$\dot{m}_{\max} = A_{\max} \cdot \dot{m}'' \quad (34)$$

The burning rate of fuel-controlled fires is difficult to predict. It is to a large extent dependent upon the nature and geometric arrangement of the fuel. Based on work conducted with wood crib fires [27], the mass burning rate over the area of the fire can be estimated using:

$$\dot{m}_{\max} = 0.0012 m_{\mathrm{tot}} \sqrt{m_{\mathrm{r}} / m_{\mathrm{tot}}} \quad (35)$$

8.5.3 Steady-burning phase

The steady-burning phase describes the period of time between the growth and decay phases, and assumes a constant heat release rate corresponding with the maximum given in 8.6.2. The duration of the steady-burning phase can be estimated, assuming the onset of decay once 80% of the fuel is consumed, with:

$$t_{\text{steady}} = \frac{0.8Q_{\text{fd}} - \left[\frac{1}{n+1}\alpha\left(t - t_{\text{i}}\right)^{n+1}\right]}{\dot{Q}_{\text{max}}} \quad (36)$$

The correlation simply describes: (a) in the numerator – the energy consumed prior to the onset of decay, less that consumed during growth, and (b) the denominator – the peak heat release rate during the fire's steady-burning phase.

Implicit within this is a conservative combustion efficiency of unity. Generally, per Law [28], the steady-burning phase would not be expected to be less than 1 200 s for most cellulosic fuels.

8.5.4 Decay

The heat release rate as a function of time during the cooling phase can be estimated assuming a linear decay after 80% of the available fuel (Q_{fd}) has been consumed. The duration of the decay phase (t_{decay}) can be estimated as:

$$t_{\text{decay}} = \frac{0.4Q_{\text{fd}}}{\dot{Q}_{\text{max}}} \quad (37)$$

8.5.5 Travelling fire frameworks

8.5.5.1 General

Real fire incidents such as those experienced in the WTC complex (2001) and large-scale experiments have illustrated that in larger enclosures, fires do not burn relatively uniformly as in smaller enclosures but tend to travel across the floor space. These fires are generally referred to as travelling fires. Travelling fires can have a significant impact on the structural response of the building as discussed in PD 7974-3. Travelling fires can be generally conceptualized as a localized fire that moves [29]. Travelling fires are generally controlled by flame spread and burning time rather than specific ventilation conditions, as fires in small compartments are.

To account for such fires, a few travelling fire (TF) methods have been put forward with a particular bias to structural design applications [30], [1], [31]. There are three common components between most of these methodologies:

a) that the heat and temperature field induced by the fire is not homogenous but split into the near field (flames) and the far field (smoke). The near field represents the burning region of the fire (with high temperatures of up to 1 200 °C and corresponding high heat fluxes) and the far field represents the region remote from the burning area where the hot smoke is moving away from the flames (lower temperatures and lower heat fluxes);

b) that the fire travels (moving both the far and the near field) at a given size and spread rate; and

c) that multiple fire sizes and fire spread rates are possible, but the occurrence of a specific size and spread is near impossible to predict ahead of time and therefore a range of possible fires should be considered together.

8.5.5.2 Relevant supporting correlations

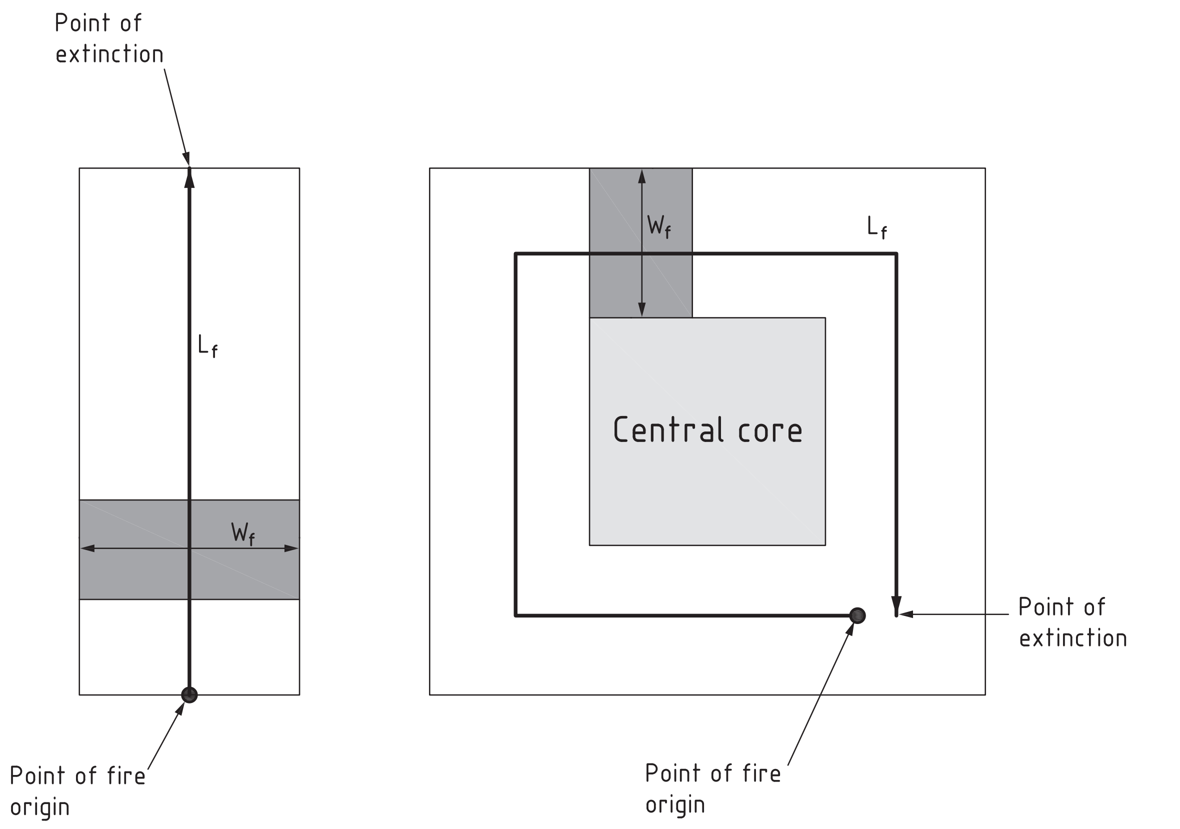
The total fire heat release rate varies with time as a function of the area of burning and the heat release rate density, as described in 8.1.3.

The area of burning evolves as a function of spread rate, local burning time and compartment geometry. The local burning time, i.e. the time taken to consume a unit area of fuel is given by:

$$t_b = \frac{Q''_{fd}}{\dot{Q}''} \tag{38}$$

This presupposes that the fire load energy density is constant within the compartment, and evenly distributed along the fire path length (L_f). Figure 6 shows two indicative fire arrangements with fire travel path lengths and path widths.

Figure 6 — *Two indicative travelling fire arrangements with fire travel path lengths and path widths*



a) Unobstructed enclosure **b) Enclosure with a central obstruction, such as a core**

The total burning duration of the fire is therefore:

$$t_{total} = (L_f / s) + t_b \tag{39}$$

The maximum heat release rate would occur when the area of fire burning is the lesser of:

$$L_f.W_f \text{ or } t_b.s.W_f \tag{40}$$

NOTE From a review of the available literature, Rackauskaite, et. al. [1], propose spread rates in the range of 0.1 mm·s^{-1} to 19.3 mm·s^{-1}.

8.6 Post-flashover fires (inclusive of decay)

8.6.1 Maximum enclosure temperature

An upper bound maximum enclosure temperature post-flashover can be estimated based upon the work of Thomas and Heselden [32], and Law [28], where:

$$T_{g(\max)} = 6000\frac{\left(1-e^{-0.1\Omega}\right)}{\sqrt{\Omega}} \quad (41)$$

with:

$$\Omega = \frac{A_t}{A_v\sqrt{H_v}} \quad (42)$$

However, if the fire load is low, there might be insufficient energy to achieve $T_{g(max)}$. Therefore, the impact of fire load on the average temperature in the compartment can be evaluated using:

$$T_g = T_{g(\max)}\left(1-e^{-0.05\psi}\right) \quad (43)$$

with:

$$\psi = \frac{m_e}{\left[A_v A_t\right]^{0.5}} \quad (44)$$

The correlations presented in this subclause are generally valid where: (a) the enclosure is of a size where flashover can be expected, (b) the enclosure linings have a thermal inertia in the range 720 J/(m^2·s$^{0.5}$·K) to 2 500 J/(m^2·s$^{0.5}$·K), and (c) Ω is in the range of 10 m$^{-0.5}$ to 50 m$^{-0.5}$.

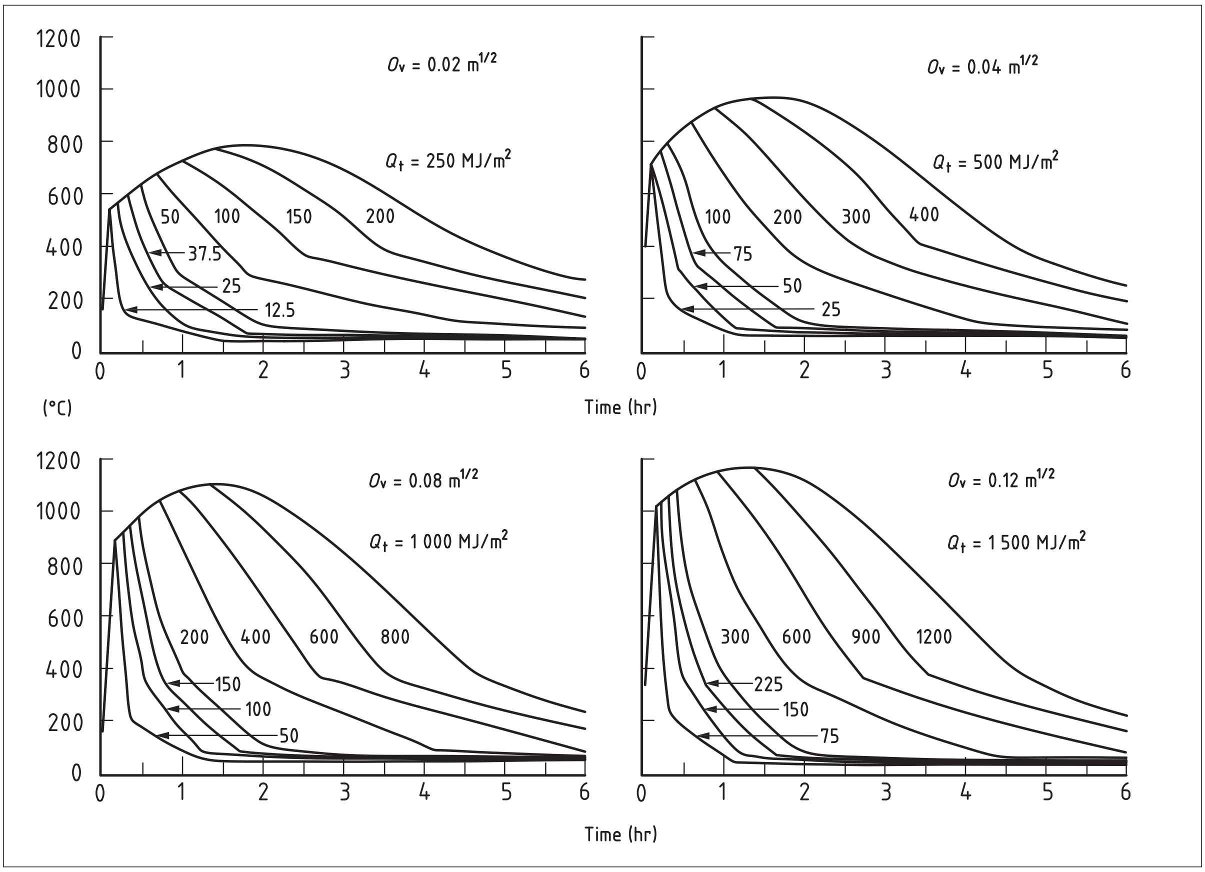
8.6.2 Time–temperature relationship

The time–temperature relationship for smaller enclosures can be calculated via computational means, e.g. using zone models such as CFAST, OZONE or B-RISK. In addition, approximations can also be made via methods such as the Parametric Fire Model documented in BS EN 1991-1-2. These models are not reproduced in this document.

Figure 7 provides indicative gas time–temperature according to Magnusson and Thelandersson [33] for compartments afforded "normal linings" [i.e. 200 mm thick concrete, brick and lightweight concrete – thermal inertia c. 1 100 J/(m^2·s$^{0.5}$·K)] as a function of fire load density and opening factor. The models underpinning Figure 7 originate from calibrations against experiments that predominantly used timber cribs as the fuel source.

$$Q_t = 18.8 m_e / A_t \text{ and } O_v = A_v\sqrt{H_v} / A_t \quad (45)$$

Figure 7 — *Example gas time-temperature curves for post-flashover fires as a function of opening factor and fire load density with normal enclosure linings*



8.7 Nominal time–temperature curves

8.7.1 General

Nominal or standard fire curves are the simplest and most commonly adopted means of representing a fire. They have been developed to allow classification and assessment of construction products using commercial furnaces. Although they do not represent "real" fire scenarios they have been developed from experience of real fires. A number of different curves exist. The choice of curve for a particular situation will depend on the end use. Different curves are used for testing and assessment depending on whether the structural element or product is to be used in the construction of a normal building (office, dwelling etc.), the petrochemical or offshore industry, or for tunnels.

8.7.2 Standard fire curve

The most well-known and widely adopted nominal fire curve is the "standard" fire given in BS EN 1991-1-2 and the ISO 834 series. The standard fire curve is based on a cellulosic (i.e. wood/paper/fabric) fire within a compartment and is described by Formula (46):

$$\theta_g = 20 + 345 \log_{10}\left(8t_m + 1\right) \quad (46)$$

8.7.3 External fire curve

An external fire curve (see BS EN 1991-1-2) is available for applications where the structural element is subject to heating from flames emerging from openings. This is a less severe exposure condition than for internal elements and takes the form:

$$\theta_g = 660(1 - 0.687e^{-0.32t_m} - 0.313e^{-3.8t_m}) + 20 \quad (47)$$

8.7.4 Hydrocarbon fire curve

In situations where the calorific value of the fire load is significantly higher than the standard cellulosic curve, such as the petrochemical or offshore industries, then a hydrocarbon fire exposure would be a more appropriate nominal fire curve to test and assess products. A number of such curves exist. The most widely used is reproduced in the fire part of the Eurocode for Actions, BS EN 1991-1-2, and takes the form:

$$\theta_g = 1080(1 - 0.325e^{-0.167t_m} - 0.675e^{-2.5t_m}) + 20 \quad (48)$$

8.7.5 Slow heating curve

For reactive fire protection products it is possible that testing under standard fire conditions overestimates performance. In such cases a slow heating curve is available of the form:

$$\theta_g = 154t_m^{0.25} + 20 \quad (49)$$

for the first 21 minutes of the test followed by the standard curve for the remaining period. However, this is rarely used in practice. See BS EN 1363-2.

8.7.6 Nominal curves for tunnel fires

In recent years a number of high-profile tunnel fires have caused great damage and loss of life. In such applications an even more severe exposure than the hydrocarbon curve may be appropriate to simulate the effect of a fire involving large petrol tankers in a confined space. The most onerous exposure has been developed in the Netherlands as the RWS curve which reaches temperatures of 1 350 °C. Other curves include the German RABT curve which achieves a maximum temperature of 1 200 °C.

8.8 Production of species

8.8.1 Yields and production rates of smoke and combustion gases

The mass yields (Y_i) of smoke particulates and combustion gases depend on the chemical composition of the fuel and the varying combustion conditions during a fire. For any specific fuel, the yields differ between non-flaming and flaming combustion conditions. For flaming combustion, yields vary considerably between well-ventilated and under-ventilated combustion conditions as a function of the equivalence ratio (φ). Products of inefficient combustion (CO, HCN, hydrocarbon and smoke particulates) increase with increasing equivalence ratio while products of efficient combustion (CO_2, H_2O, NOx, SO_2) decrease with increasing equivalence ratio. The yields of halogen acid gases remain approximately constant across the φ range. The relationship between equivalence ratio and yields for burning fuels are sigmoid, showing major changes in the range between φ 1 to 1.5, but relatively minor changes below φ 1 and above φ 1.5. Empirical relationships vary somewhat between individual fuels (see Purser [34]) and some further reactions can occur between components in fuel mixtures. Available data on interactions are currently limited, but are considered unlikely to be of major significance, so that estimates for yields from fuel mixtures can be based on the relationships for each fuel component.

For simplified design calculations it is therefore reasonable to use yield data for two basic flaming fire states, well-ventilated combustion (φ <1) and under-ventilated combustion (φ >1). In general, well-ventilated combustion occurs for open burning fires outside and during fires that are small in relation to the enclosure volume, height and ventilation, so that the flames do not penetrate the upper smoke later. This applies to the first few minutes of enclosure fires, and during fires in tall atrium spaces. Flaming fires in single-storey enclosures (such as dwellings, offices and small retail units) generally become under-ventilated within a few minutes as flames penetrate the upper layer and as the equivalence ratio exceeds 1. Yields might be somewhat further increased in under-ventilated post-flashover fires.

The mass production rates of smoke and combustion gases for any fuel then depend on the yields under the prevailing combustion conditions (kg/kg) and the mass burning rate of the fuel (kg/s).

Data for smoke and combustion gas yields under well-ventilated and under-ventilated flaming combustion conditions measured for 14 materials commonly used in buildings is presented in Annex B.

Calculation expressions for yields and mass production rates for smoke and combustion gases are presented in **8.8.2** and **8.8.3**.

8.8.2 Smoke mass production, yields and concentrations

The mass rate of smoke production can be found using:

$$\dot{m}_{\mathrm{part}} = \varepsilon_{\mathrm{smoke}} \dot{m}_{\mathrm{f}} \qquad (50)$$

Table B.2 to Table B.5 give smoke particulate (soot) yield (also known as smoke mass conversion factors) data. Data for a range of individual materials burned under well-ventilated and under-ventilated flaming combustion conditions are presented in Table B.2 and Table B.5. Table B.4 shows generic data for cellulosics, plastics and general building contents. Further data for cellulosics and plastics under flaming and non-flaming conditions are given in Table B.3.

The findings from these data, obtained by different authors using different experimental scenarios are described and discussed in Annex B. Since the mass of fuel carbon converted to smoke particulates in fires is low, small variations in combustion efficiency arising from the local combustion conditions in different fires can result in some variations between particulate yields, especially for well-ventilated fires for which the yields are very low, especially for cellulosic materials.

As an alternative to expressing smoke yield in terms of soot particulate yield, it can be expressed in optical terms as mass optical density and (D_{m}) or expressed to the base *e* as the Specific Extinction Area A_{SEA} ($\mathrm{m^2 \cdot kg^{-1}}$) where $A_{\mathrm{SEA}} = 2.3 \times D_{\mathrm{m}}$.

Values for A_{SEA} for a range of common materials for well-ventilated and under-ventilated flaming combustion are given in Table B.2. Table B.4 gives data for A_{SEA} and D_{m} for well- ventilated flaming combustion for generic cellulosics, plastics and general building contents. Table B.5 gives further data for A_{SEA} and D_{m} for a range of common fuels under well-ventilated flaming conditions. These optical measures yield depend primarily on the particulate mass yield, but also partly on the colour and particle size distribution in the smoke. The measured value is also sensitive to the method of measurement. Two relevant aspects are the use of polychromatic or monochromatic light and the wavelength for monochromatic light. White light sources are subject to forward light scattering, giving different results from monochromatic red light from a He-Ne laser (wavelength 0.649 µm) which is now used for most test methods.

Both large- and bench-scale test procedures tend to monitor the optical/obscurational properties of smoke. However, the mass concentration of smoke is useful (e.g. for input to field and zone computational models). A relationship between optical properties and mass concentration has been developed for post-flame generated smoke for a range of fuels under well-ventilated conditions [35]. Bouguer's law is the basis, relating the ratio of the transmitted and incident intensities to the mass concentration, c_s, of the smoke, the path length, L, through the smoke and the specific mass extinction coefficient, K_m, using Formula (51):

$$I / I_o = exp\left(-K_m \cdot c_s \cdot L_s\right) \tag{51}$$

where:

K_m is the specific extinction coefficient ($m^2 \cdot g^{-1}$)

c_s is the smoke particulate mass concentration ($g \cdot m^{-3}$)

L_s is the path length (m)

The estimated mean value for K_m is 8.7 $m^2 \cdot g^{-1}$ with an expanded uncertainty at the 95% confidence interval of 1.1 $m^2 \cdot g^{-1}$. K_m therefore represents a conversion factor between smoke yield and specific extinction area:

$$A_{SEA} / \varepsilon_{smoke} = 8.7 \times 1000 \tag{52}$$

or smoke yield and mass optical density:

$$D_m / \varepsilon_{smoke} = \left(8.7 \times 1000\right) / 2.3 \tag{53}$$

The value of 8.7 $m^2 \cdot g^{-1}$ becomes 10 $m^2 \cdot g^{-1}$ when corrected from He-Ne laser light to visible light and it depends on the smoke produced being primarily carbonaceous soot. The value is stated to be smaller and more variable for smoke generated under smouldering or pyrolytic conditions as a result of the low light absorption of this type of smoke and variability in smoke droplet size. Soot yields obtained during under-ventilated burning of polymeric fuels in a small-scale apparatus have been shown to be higher than those under well-ventilated conditions by a factor of approximately 2 ±0.5.

For the material data set in Table B.2, the average for $A_{SEA} / \varepsilon_{smoke} = 4.8$ (standard deviation 1.45) for well-ventilated flaming and 7.1 (standard deviation 1.29) for under-ventilated flaming. These ratios are somewhat lower than those obtained by Mulholland [35], and might be due to the use of a white light emitter rather than a red laser. A human viewing incident or reflected light through smoke might be subject to similar effects, adding to the uncertainty relating to human perception of smoke obscuration.

8.8.3 Gas species mass production, yields and concentrations

8.8.3.1 Gas species mass production

An estimate of the mass rate of production of a gaseous product by a fire may be made using Formula (54):

$$\dot{m}_i = Y_i \dot{m}_f \tag{54}$$

NOTE Limits. For most design purposes, the mass rate of smoke and carbon monoxide production are proportional to the rate of heat release in a flaming fire and can be determined from Formulae (50) and (54) respectively; however, this is not necessarily justified for a smouldering, under-ventilated or suppressed fire. In these situations, the mass rate of carbon monoxide and smoke production can increase in relation to the rate of heat release.

8.8.3.2 Gas species mass yields

Species mass yield data for carbon monoxide and other gas species under well-ventilated flaming are listed in Table B.2. Data on Y_{co} for well-ventilated and under-ventilated flaming of some generic materials are given in Table B.4 and for some specific well-ventilated materials in Table B.5.

Based on the data in Table B.4 and Table B.5, in general terms, the CO yield (Y_{co}) can be approximated as 0.013 kg/kg for well ventilated flaming (φ <1) and 0.2 kg/kg for under ventilated flaming (φ >1).

8.9 Activation of heat detector devices and automatic fire suppression systems

The time to operation of a heat detector or heat sensing element of an automatic fire suppression system (e.g. sprinkler head) can be estimated from the differential equation proposed in Heskestad and Bill [36]:

$$\frac{d(\Delta T_e)}{dt} = \frac{u^{1/2}}{RTI}[\Delta T_g - (1 + C / u^{1/2})\Delta T_e \qquad (55)$$

Tsui and Spearpoint [37] quote C factors in the range of 0.33 – 0.65 $(m/s)^{1/2}$ depending upon the response type. RTI values are given in the literature, e.g. [38]. The rated temperature, permitting calculation of ΔT_e, can be found in the relevant manufacturer's specifications.

8.10 Effect of automatic fire suppression systems on fire conditions

Automatic fire suppression systems can control, and sometimes reduce, the growth and spread of a fire. Accordingly, fires starting within enclosures containing such systems might be considered controlled within an area of burning consistent with the spatial configuration of the suppression system. Realistic and relevant assumptions should be made on the efficacy of sprinkler systems to limiting potential fire growth and fire spread. For solid fuel sources, it might be suitable to assume that the fire spread is limited to within the area of activated sprinkler heads.

Suppression systems that actively introduce cooling effects into the enclosure, e.g. water-based, can reduce the severity of a fire in terms of enclosure temperatures. This effect is difficult to quantify, although it is often assumed that the heat release rate of the fire remains fixed at the point at which the system is first activated. Alternatively, Evans [39] proposes a means of quantifying the impact of sprinkler suppression on a fire's heat release via the following, which applies to unshielded fires:

$$\dot{Q}(t - t_{act}) = \dot{Q}(t_{act}) exp\left[\frac{-(t - t_{act})}{3(\dot{w}'')^{-1.85}}\right] \qquad (56)$$

The presumption of sprinkler control or subsequently suppression in all applications is not appropriate. The inclusion of the sprinkler interaction with fire development should be done in cognizance of risk. Treatment in the probabilistic sense is discussed in PD 7974-7.

Annex A (informative) Reference data

The following data in Table A.1 to Table A.6 is provided for informative purposes. It is incumbent on the user, in cognizance of the recommendations set out in **4.2**, to select data that is appropriate for the given application.

Table A.1 — *Convective fractions for different fuels [12]*

Fuel	Convective fraction (-)
Wood (Douglas fir)	0.62
PMMA	0.69
PE	0.57
PS	0.41
PU (rigid foam)	0.42
Propane	0.71
Methane	0.86

Table A.2 — *Standardized fire growth rates [BS ISO/TR 13387-2]*

Growth rate	α (kW/s^n)	n (-)
Slow	0.003	
Medium	0.012	2
Fast	0.047	
Ultra-fast	0.188	

Table A.3 — *Fire growth rates for some discrete fuel assemblies*

Growth rate	α (kW/s^n)	n (-)	References
Cars – engine bay fire	0.01 to 0.06	2	[17]
Office reception workstation	0.003		
Wood frame chairs	0.008 to 0.017		
Stacked pallets	0.01		
Double bed	0.08		
Racked goods	0.0448 (per tier)	3	[40]
Upholstered furniture and stacked furniture near combustible linings	0.188	2	BS ISO/TR 13387-2
Office furniture — horizontally distributed	0.012		
Floor coverings	0.003		
Cardboard or plastic boxes in vertical storage arrangement	0.188		
Bedding	0.047		

Table A.4 gives $\dot{Q}''$ for different occupancies. For most cases, $\dot{Q}''$ corresponds with maximum value estimated over the full duration of a fire. For hotels and industrial buildings, $\dot{Q}''$ corresponds with the mean value estimated over a defined period of burning.

Table A.4 — *Heat release rates per unit area for different occupancies [41]*

Occupancy	$\dot{Q}''$ (kW/m²)	References
Shops	270–1 000 (maximum)	Ghosh [42], Hinkley [43] and Law [44]
Offices	150–650 (maximum)	Ghosh [42]
Hotel rooms	250 (average)	Hansell and Morgan [45]
Residential	320–570 (maximum)	Fang and Breese [46]
Industrial	90–620 (average)	Theobald [47]
Storage/stacked commodities	400–20 000 (maximum)	Alpert and Ward [48] and Delichatsios [49]

Table A.5 gives fire load densities for a range of occupancy types. Parameters describing the fire load distributions are also given.

Table A.5 — *Fire load density for different occupancies*

Occupancy	Distribution type	Mean Q''_{fd} (MJ/m²)	Coefficient of variation (-)	References
Dwelling		780		
Hospital		230		
Hotel room	Gumbel type I	310	0.30	[50]
Library		1 500		
Office		420		
School		285		
Fast food outlet		526	0.61	
Clothing store		393	0.42	
Restaurant		298	0.64	[51]
Kitchen		314	0.51	
Retail unit storage area	Log-normal	1 196	1.01	
Manufacturing and storage of combustible goods (<150 kg/m²)		1 180	0.73	[52]
Manufacturing and storage of combustible goods (>150 kg/m²)		9 920	0.86	

Table A.6 shows the effective emission co-efficient for various materials.

Table A.6 — *Effective emission co-efficient, K, for various materials*

Material	Effective emission coefficient, *K* m^{-1}
Wood cribs	0.51 [12] to 1.1 [53]
Assorted furniture	1.13 [12]
Diesel oil	0.43 [54]
Polypropylene	1.8 [55]
Polystyrene	5.3 [55]
PMMA	1.3 [55]
Kerosene	2.6 [54]
Petrol	2.0 [54]
Alcohol	0.37 [54]

Annex B (informative) Reference data for smoke and toxic gas yields

B.1 Data for smoke and toxic gas yields for materials under well-ventilated and under-ventilated flaming conditions

Data for smoke and combustion gas yields under well-ventilated and under-ventilated flaming combustion conditions measured for 14 materials commonly used in buildings is presented in Table B.1 and Table B.2 from Purser [34]. Table B.1 shows the net heat of chemical combustion, stoichiometric oxygen demand and elemental composition of each fuel material.

Table B.1 — *Composition of test materials*

Material	$\Delta H_{c,eff}$	Ψ_0 [A)]	Elemental composition (%)							
	kJ.g^{-1}	g.g^{-1}	C	H	O	N	Cl	Br	P	S
Bouclé acrylic/wool/polyester 38/38/24 mixed fibre fabric	26.5	2.02	63.1	6.4	16.7	12.89	-<0.3	<0.5	–	0.94
Bouclé acrylic/wool/polyester 38/38/24, FR back-coated	25.0	1.91	59.0	6.3	16.1	10.83	0.95	6.09	–	0.76
CMHR[A)] polyurethane foam- FR	24.5	1.87	56.45	7.67	24.1	8.22	2.53	–	–	–
Low density polyethylene (LDPE)	44.8	3.42	85.5	14.51	–	–	–	–	–	–
Medium density fibreboard (MDF)	16.9	1.35	47.90	6.13	41.66	3.69	0.62	<0.5	<0.01	-
Polyacrylonitrile (>85%) fabric	30.5	2.33	65.62	5.71	–	23.24	–	–	–	–
Polyamide 6	30.5	2.33	63.68	9.79	14.14	12.4	–	–	–	–
Polyisocyanurate PIR rigid foam	24.5	1.87	63.5	4.98	21.8	6.15	3.56	–	–	–
Polymethylmethacrylate PMMA	25.2	1.92	60.33	8.14	31.53	–	–	–	–	–
Polystyrene	40.2	3.07	92.26	7.38	–	–	–	–	–	–
Polyvinylchloride PVC	16.8	1.28	38.44	4.84	–	–	56.73	–	–	–
Plywood	17.8	1.36	46.32	5.80	47.56	0.32	-	–	–	–
Acrylic/cotton/polyester 52/31/17 velour mixed fibre fabric	26.2	2.00	64.4	6.39	18.45	11.55	<0.3	<0.5	–	–
Wood *Pinus sylvestris*	18.1	1.38	49.2	6.44	44.22	0.14	–	–	–	–

Table B.1 *(continued)*

Material	$\Delta H_{c,eff}$	Ψ_0 [A)]	Elemental composition (%)							
	kJ.g^{-1}	g.g^{-1}	C	H	O	N	Cl	Br	P	S

[A)] CMHR = combustion modified high resilience polyurethane foam FR (flame retarded)

Table B.2 shows the yields of smoke and combustion gases measured from each material under well-ventilated flaming combustion conditions (φ ~ 0.5) and under-ventilated combustion conditions (φ 1.5 to 2.0). Smoke yields are expressed in mass terms (mg smoke particulates/g fuel mass burned) and in terms of visibility as smoke extinction area (A_{SEA}) (= 2.3 × D_m) (m^2·kg). The average ratio between A_{SEA} and particulate yield was 4.8 for well-ventilated fires and 7.1 for under-ventilated fires.

Table B.2 — *Toxic gas yields, effective heats of combustion and oxygen consumption under well-ventilated and under-ventilated combustion conditions for a range of common polymeric materials from the PD ISO/TS 19700 tube furnace [34]*

Well ventilated flaming: φ 0.4–0.8														
Polymer	φ	**Eff Ht** kJ/g	**CO_2** mg/g	**CO** mg/g	**HC** mg/g	**O_2** [A)] mg/g	**ε_{smoke}** kg/kg	**A_{SEA}** m^2/kg	**HCN** mg/g	**NO** mg/g	**NO_2** mg/g	**HCl** mg/g	**HBr** mg/g	**SO_2** mg/g
LDPE[B)]	0.49	41.5	2836	15	85	3166	0.045	268	–	–	–	–	–	–
Polystyrene	0.49	31.6	2644	61	82	2416	0.110	621	–	–	–	–	–	–
Wood	0.51	16.9	1696	6	13	1293	0.005	12	–	–	–	–	–	–
Plywood	0.52	17.3	1774	6	11	1324	0.003	1	0	2	1	–	–	–
MDF[C)]	0.49	16.8	1680	7	24	1283	0.003	7	0	3	1	–	–	–
PAN[D)]	0.88	30.4	2339	39	54	2320	0.025	104	8	2	1	–	–	–
Polyamide 6	0.51	28.4	2216	3	34	2166	0.019	147	0	11	1	–	–	–
PIR[E)]	0.52	24.6	2340	48	13	1874	0.033	75	3	2	1	69	–	–
PMMA	0.52	24.7	2192	5	13	1881	0.023	148	0	–	–	–	–	–
CMHR PU[F)]	0.59	25.3	2156	41	48	1928	0.028	154	4	3	1	9	–	–
Bouclé non-FR[G)] Acrylic, wool, PE 34/38/24	0.50	24.4	2128	60	19	1861	0.026	103	1	7	1	–	–	12
Bouclé FR[G)]	0.44	19.3	1486	130	81	1474	0.090	456	19	8	0	10	30	11
Velour[H)] Acrylic, cotton,PE 52/31/17	0.52	26.3	2240	41	51	2005	0.019	84	2	4	0	–	–	–
PVC[I)]	0.40	10.7	667	177	70	815	0.032	163	–	–	–	447	–	–
Fuel rich (under-ventilated) flaming φ 1.5–2.0														
LDPE	1.71	29.4	1696	196	334	2242	0.085	668	–	–	–	–	–	–
Polystyrene	1.99	21.8	1662	86	299	1664	0.179	820	–	–	–	–	–	–
Wood	1.71	9.8	967	134	80	752	0.019	155	–	–	–	–	–	–
Plywood	1.54	9.4	986	96	55	714	0.014	120	0	1	0	–	–	–
MDF	1.66	8.9	870	113	62	681	0.019	150	3	1	1	–	–	–
PAN	1.69	19.1	1271	130	235	1460	0.060	489	72	2	3	–	–	–
Polyamide 6	2.03	16.3	1135	130	248	1246	0.051	413	41	3	3	–	–	–
PIR	2.08	14.0	937	333	136	1068	0.072	495	20	1	2	57	–	–
PMMA	2.06	14.0	1108	239	260	1067	0.021	173	0	–	–	–	–	–

Table B.2 *(continued)*

Well ventilated flaming: φ **0.4–0.8**															
Polymer	φ	**Eff Ht** kJ/g	$\mathbf{CO_2}$ mg/g	**CO** mg/g	**HC** mg/g	$\mathbf{O_2}$ [A)] mg/g	ε_{smoke} kg/kg	A_{SEA} m^2/kg	**HCN** mg/g	**NO** mg/g	$\mathbf{NO_2}$ mg/g	**HCl** mg/g	**HBr** mg/g	$\mathbf{SO_2}$ mg/g
CMHR PU	2.07	14.9	1041	246	197	1134	0.059	403	14	1	2	5	–	–
Bouclé non-FR	2.12	14.2	1138	119	228	1080	0.104	594	35	1	2			4
Bouclé FR	2.03	13.3	920	146	184	1016	0.100	611	25	2	1	3	28	8
Velour	2.06	14.0	1211	126	239	1071	0.084	526	34	2	1	–	–	–
PVC	1.82	7.5	389	137	98	573	0.070	473	–	–	–	585	–	–

A) Oxygen consumed (mg/g)

B) LDPE low density polyethylene

C) MDF medium density fibreboard

D) PAN polyacrylonitrile

E) PIR polyisocyanurate foam

F) CMHR = combustion modified high resilience polyurethane foam FR (flame retarded)

G) Bouclé looped yarn mixed fabric (see Table B.1)

H) Velour mixed fabric (see Table B.1)

I) PVC polyvinylchloride (rigid 100% PVC)

B.2 Smoke particulate yields (smoke mass conversion factors)

Particulate smoke (soot) yields (also known as mass conversion factors) for a range of materials under well-ventilated and under-ventilated flaming combustion conditions are presented in Table B.2 from Purser [34]. Further generic data for cellulosics and "plastics" under flaming and non-flaming conditions are given in Table B.3 [56].

Table B.3 — *Smoke mass conversion factor [56]*

Material	**Smoke particulate yield,** ε_{smoke} kg/kg	
	Flaming	**Non-flaming**
Cellulosics	<0.01 to 0.025	0.01 to 0.17
Plastics	<0.01 to 0.17	<0.01 to 0.19

NOTE Limits. The requirement of a well-ventilated fire is emphasized. Below concentration of 12% to 15% O_2*, smoke yield can increase. Even in the well-ventilated region, smoke yield is dependent on the scenario and the equivalence-ratio.*

Those for flaming (0.01 kg/kg to 0.025 kg/kg) in Table B.3 compare with an average of 0.034 and a range of 0.003 kg/kg to 0.11 kg/kg from Table B.2. For under-ventilated flaming the yields in Table B.2 are approximately double those from well-ventilated flaming (average 0.07 kg/kg, range 0.14 to 0.18).

For optical smoke measurements, values of A_{SEA} for a range of common materials are also given in Table B.2. Table B.4 compares ranges of data for CO, particulate smoke and optically measured smoke yields for generic products compiled from Table B.2 with data for CO and particulate yields from Tewarson [57] and for smoke particulate yields, smoke extinction area (A_{SEA}) and mass optical density (D_m) from Mulholland [35]. Table B.5 shows further CO and smoke data for well-ventilated combustion for individual materials. Data for A_{SEA} and D_m are shown as calculated from Tewarson's particulate data according to Formulae (51) and (52) and as measured by Mulholland for similar materials.

The data in Table B.2 to Table B.5 show good agreement between the CO and particulate yields for individual materials and generic material classes for the results from all three authors, (Purser, Mulholland and Tewarson), but some variation between optically based measurements and calculation of smoke yields (expressed as A_{SEA} or D_m $m^2 \cdot kg$). Since the optical measurement of Purser [34] used a white light source rather than a red He-Neon laser, the more conservative (higher) optical density measurement data from Mulholland [35] may be considered more applicable. The results show that well-ventilated yields of CO and smoke vary considerably between different materials, tending to be higher for "plastics" than for cellulosic materials. The results from Table B.2 and Table B.4 also show that yields of both CO and smoke increase considerably as combustion conditions become under-ventilated.

For under-ventilated flaming conditions the CO yields are sensitive to upper layer temperature, equivalence ratio and flame region oxygen concentration, so can be closer to 0.2 kg/kg in some compartment fires, especially post-flashover.

Table B.4 — *Ranges of carbon monoxide yields, smoke particulate yields, smoke specific extinction areas and mass optical densities for cellulosics and plastics under well-ventilated and under-ventilated flaming combustion*

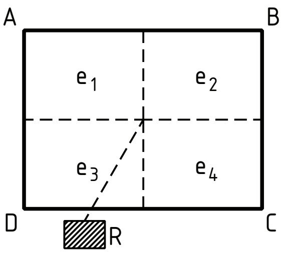
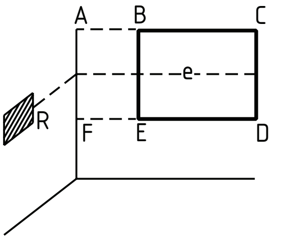
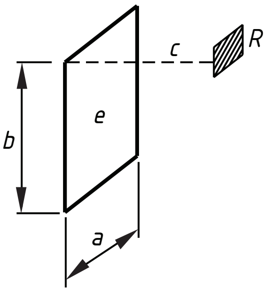
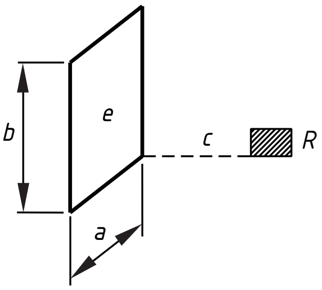
Fuel type and author		Y_{CO} **kg/kg**	ε_{smoke} **kg/kg**	A_{SEA} **m²/kg**	D_m **m²/kg**
Purser [34]					
Cellulosics	Well-ventilated	0.005 to 0.007	0.003 to 0.005	7 to 15.2	3 to 7
	Under-ventilated	0.055 to 0.080	0.014 to 0.019	120 to 155	52 to 67
Plastics	Well-ventilated	0.003 to 0.177	0.019 to 0.110	75 to 621	33 to 270
	Under-ventilated	0.086 to 0.333	0.059 to 0.179	403 to 820	175 to 356
Mulholland [35] (smoke optical) and Tewarson (CO) and smoke particulates [57]					
Cellulosics	Well-ventilated	0.004	<0.01 to 0.025	920	400
Plastics	Well-ventilated	0.024 to 0.063	<0.01 to 0.17	552 to 2300	240 to 1000
General building contents	Well-ventilated	0.013		690	300

NOTE Limits [35]. Investigations have shown that the correlation between small-scale and large-scale tests breaks down as the fire becomes more complex. In large-scale tests, heat flux and ventilation conditions can have a major impact on smoke production. In a design procedure, a sensitivity analysis is necessary.

Table B.5 — *Carbon monoxide yields, smoke particulate yields, smoke specific extinction areas and mass optical densities for well-ventilated combustion from Tewarson [57] and Mulholland [35]*

Material	Y_{CO} kg/kg	ε_{smoke} kg/kg	A_{SEA} m²/kg Calculated	A_{SEA} m²/kg Measured	D_m m²/kg Calculated	D_m m²/kg Measured
Plywood	–	–	–	668	–	290
PMMA	0.010	0.022	191	345	83	150
PVC (with plasticizer)	0.063	0.172	1496	1474	650	640
Douglas fir	0.004	0.015	131	645	57	280
Polystyrene	0.060	0.164	1427	1819 to 3224	620	790 to 1400
Polyurethane (rigid)	0.024	0.113	983	597 to 760	427	220 to 330
Ethanol	0.001	0.008	70	–	–	–
Kerosene	0.012	0.042	365	–	–	–
Benzene	0.067	0.181	1575	–	–	–
Octane	0.011	0.038	331	–	–	–
Silicone	0.006	–	–	–	–	–

Annex C (informative)
Example configuration factors

Geometry	**Configuration factor $F_{e\text{-}R}$**
	$F_{\text{ABCD-R}} = F_{\text{e1-R}} + F_{\text{e2-R}} + F_{\text{e3-R}} + F_{\text{e4-R}}$
	$F_{\text{e-R}} = F_{\text{ACDF-R}} - F_{\text{ABEF-R}}$
	$F_{\text{e-R}} = \frac{1}{2\pi}\left\{\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right)+\frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right\}$ where $X = \frac{a}{c}$ $Y = \frac{b}{c}$
	$F_{\text{e-R}} = \frac{1}{2\pi}\left\{\tan^{-1}\left(\frac{1}{Y}\right) - AY\tan^{-1}A\right\}$ where $X = \frac{a}{b}$ $Y = \frac{c}{b}$ $A = \frac{1}{\sqrt{X^2+Y^2}}$

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