



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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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
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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This part of PD 7974 supersedes PD 7974-1:2003, which is withdrawn.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	$\text{kW}\cdot\text{s}^{-n}$	Fire growth rate parameter
C	$(\text{m/s})^{0.5}$	Conduction factor
c_{ig}	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	Specific heat capacity of the ignition material
$c_{\text{p},0}$	$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	Specific heat capacity of ambient air
$c_{\text{p},s}$	$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	Specific heat capacity of the enclosure boundaries
c_{s}	$\text{g}\cdot\text{m}^{-3}$	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
$\varepsilon_{\text{smoke}}$	–	Proportion of smoke particulate mass yield to fuel mass loss
FTP	–	Flux-time product
g	$\text{m}\cdot\text{s}^{-2}$	Acceleration due to gravity
h_{k}	$\text{kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	Effective heat transfer coefficient of the enclosure
ΔH_{c}	$\text{kJ}\cdot\text{kg}^{-1}$	Total heat of combustion

Symbol	Unit	Description
$\Delta H_{\text{c,eff}}$	$\text{kJ}\cdot\text{kg}^{-1}$	Effective heat of combustion of fuel
H_v	m	Height of ventilation opening
k_{ig}	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Thermal conductivity of the ignition material
k_s	$\text{kW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	Thermal conductivity of the enclosure boundaries
K	m^{-1}	Effective emission coefficient
K_m	$\text{m}^2\cdot\text{g}^{-1}$	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
$\dot{m}''$	$\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$	Mass burning rate of fuel
m_e	kg	Equivalent fire load as wood
$\dot{m}_f$	$\text{kg}\cdot\text{s}^{-1}$	Mass loss rate of fuel
$\dot{m}_i$	$\text{kg}\cdot\text{s}^{-1}$	Mass rate of species production
$\dot{m}_{\text{max}}$	$\text{kg}\cdot\text{s}^{-1}$	Maximum mass burning rate
$\dot{m}_{\text{part}}$	$\text{kg}\cdot\text{s}^{-1}$	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	$\text{m}^{1/2}$	Opening factor
$\dot{q}''_{\text{crit}}$	$\text{W}\cdot\text{m}^{-2}$	Critical heat flux
$\dot{q}''_e$	$\text{W}\cdot\text{m}^{-2}$	Exposed heat flux
$\dot{q}''_R$	$\text{kW}\cdot\text{m}^{-2}$	Radiative heat flux
$\dot{Q}$	kW	Total heat release rate
$\dot{Q}''$	$\text{kW}\cdot\text{m}^{-2}$	Total heat release rate per unit area
$\dot{Q}^*$	–	Dimensionless heat release rate
$\dot{Q}_{\text{line}}^*$	–	Modified dimensionless heat release rate for line-shaped fire
$\dot{Q}_{\text{rect}}^*$	–	Modified dimensionless heat release rate for rectangular fire footprint
$\dot{Q}_c$	kW	Convective heat release rate
$\dot{Q}'_c$	$\text{kW}\cdot\text{m}^{-1}$	Convective heat release rate per unit length
Q''_{fd}	$\text{kJ}\cdot\text{m}^{-2}$	Fire load energy density
Q_{fd}	kJ	Fire load energy
$\dot{Q}_{\text{fo}}$	kW	Heat release rate to cause flashover temperature rise
$\dot{Q}_{\text{max}}$	kW	Maximum heat release rate
$\dot{Q}_R$	kW	Radiative heat release rate

Symbol	Unit	Description
$\dot{Q}_{\text{steady}}$	kW	Steady phase heat release rate
$\dot{Q}(t - t_{\text{act}})$	kW	Heat release rate post sprinkler activation
$\dot{Q}(t_{\text{act}})$	kW	Heat release rate at the time of activation
RTI	$(\text{m}\cdot\text{s})^{0.5}$	Response time index of heat sensing element
r	m	Radial distance from the ceiling impingement point
ρ_0	$\text{kg}\cdot\text{m}^{-3}$	Density of ambient air
ρ_s	$\text{kg}\cdot\text{m}^{-3}$	Density of the enclosure boundaries
ρ	$\text{kg}\cdot\text{m}^{-3}$	Density of the material
s	$\text{m}\cdot\text{s}^{-1}$	Constant fire spread rate along a linear path
σ	$\text{kW}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$	Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ kW}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$)
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
$T_{g(\text{max})}$	°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
$\bar{\theta}_{\text{cl}}$	°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
$\bar{u}_{\text{cl}}$	$\text{m}\cdot\text{s}^{-1}$	Mean centreline gas velocity
u_{cj}	$\text{m}\cdot\text{s}^{-1}$	Gas velocity in the ceiling jet
ϕ	–	Configuration factor
$\dot{w}''$	$\text{mm}\cdot\text{s}^{-1}$	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

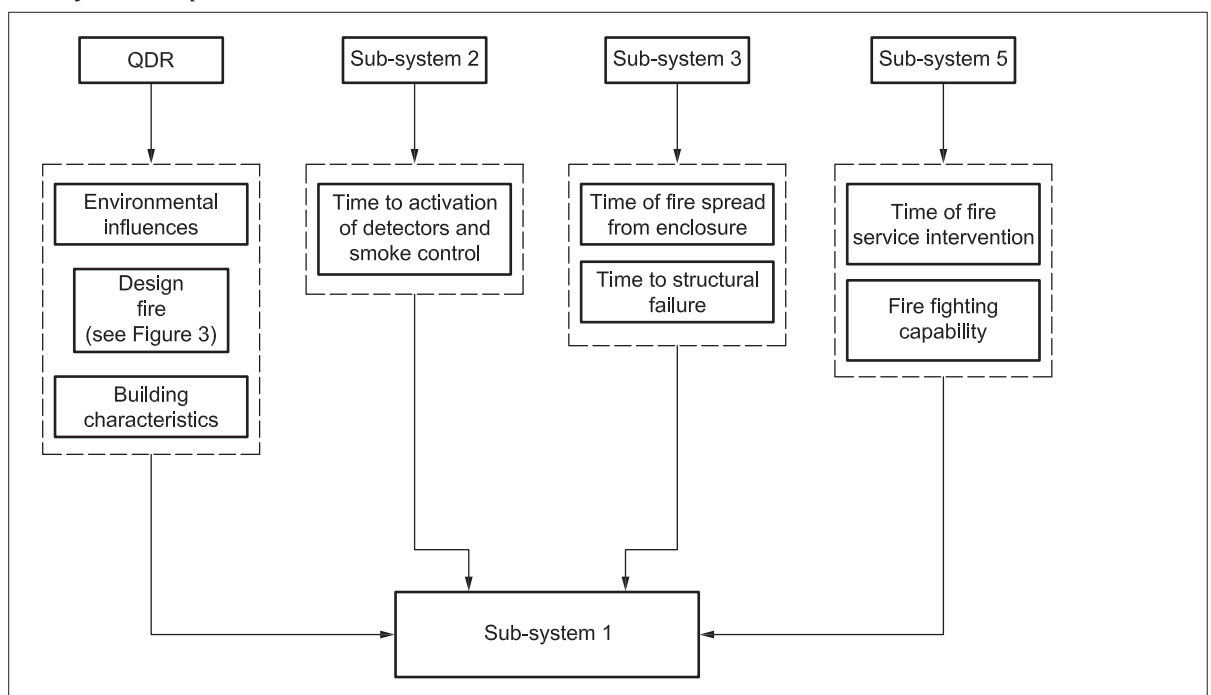
Information on environmental influences will be provided from the QDR and consideration should be given to how environmental conditions (which might be dynamic) can influence fire growth, spread and the extinguishment process, mass and heat transfer, and enclosure pressure. These might include:

- a) internal and external temperatures;
- b) internal and external air movement;
- c) internal and external oxygen concentrations.

5 Inputs

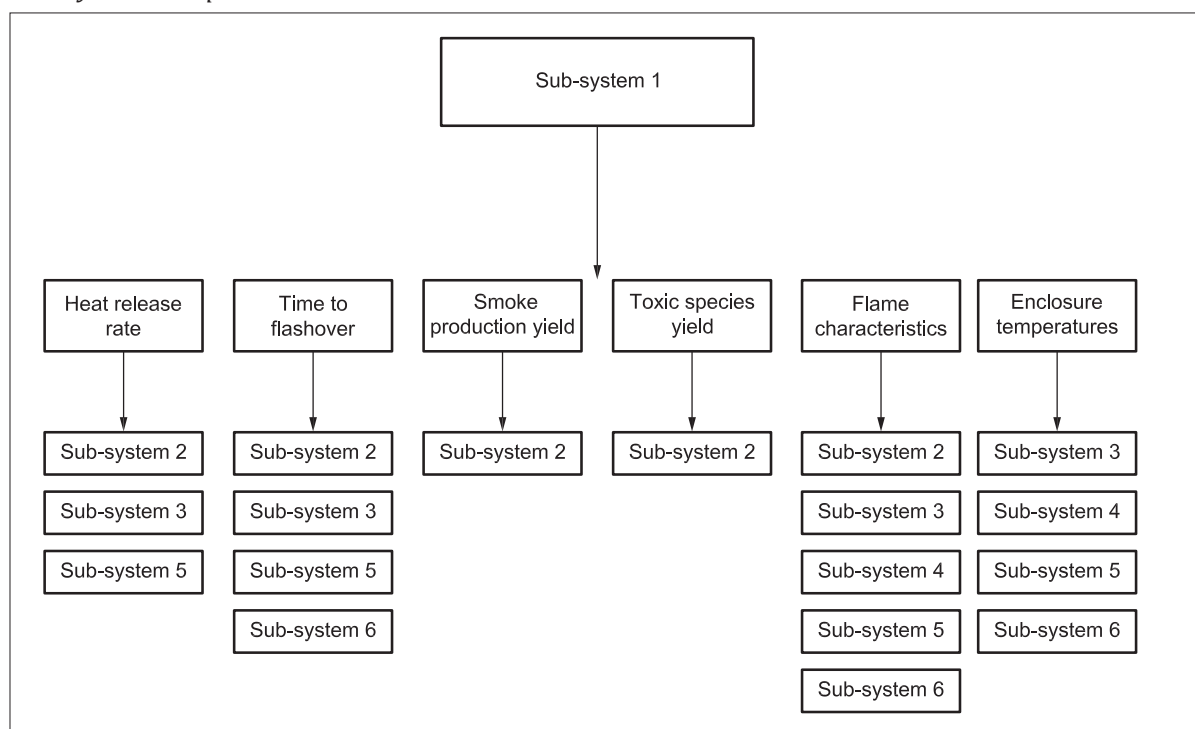
The inputs given in Sub-system 1 are illustrated in [Figure 1](#).

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:

- ignition;
- flame spread;
- growth;
- fully developed fire: localized, flashover or travelling;
- decay; and
- 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.