

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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Contents

	Page
Committees responsible	Inside front cover
Foreword	ii
Introduction	1
1 Scope	3
2 Normative references	3
3 Terms and definitions	3
4 Symbols and abbreviations	5
5 Design approach	8
6 Inputs	16
7 Outputs	17
8 Analysis	17
Annex A (informative) Experimental data	46
Bibliography	67
Figure 1 — Overview of the PD 7974 series of Published Documents	2
Figure 2 — Sub-system interactions	10
Figure 3 — Flow chart showing the initial steps that should be taken in the process of selecting fires appropriate to a particular design	11
Figure 4 — Calculation process of time to flashover	14
Figure 5 — Sub-system 1 inputs	16
Figure 6 — Sub-system 1 outputs	17
Figure 7 — Conceptual illustration of continuous fire growth	20
Figure 8 — Fire growth in an uncontrolled room fire	20
Figure 9 — Heat release rate curves for uncontrolled fires	21
Figure 10 — Effect of suppression	23
Figure 11 — Effect of partial suppression	24
Figure 12 — Burning rate and flame heights for various hydrocarbon pool fires [36]	44
Table 1 — Checklist of factors to be considered when defining a design fire	15
Table 2 — Fire growth parameters [6]	26
Table 3 — Design fire growth rates	26
Table 4 — Suggested heat release rates per unit area for fuel bed controlled fires	26
Table 5 — Experimental enclosure quoted by McCaffrey <i>et al.</i> [12]	30
Table 6 — Effective emission co-efficient, K , for various materials	32
Table 7 — Smoke mass conversion factors [25]	33
Table 8 — Fire products from well ventilated flaming combustion [25], [2]	35
Table 9 — Fire products from well-ventilated flaming combustion from Tewarson [2] and Mulholland [25]	36
Table 10 — Gross heat of combustion values for woods [30]	37
Table 11 — Percentage of all fires that are attributable to malicious fires for a range of building types	44
Table A.1 — Pillows	46
Table A.2 — Wardrobes	47
Table A.3 — Television sets	47
Table A.4 — Stored commodities	48
Table A.5 — Artificial trees	49
Table A.6 — Real trees undecorated and untreated	49
Table A.7 — Real trees decorated	49

	Page
Table A.8 — Furniture series 1: Description of commercially available products [46]	53
Table A.9 — Furniture series 1 tested in the ISO 9705 room-corner test	51
Table A.10 — Furniture series 2: Description of “made up” products tested	52
Table A.11 — Furniture series 2 tested in the ISO 9705 room-corner test	52
Table A.12 — Furniture series 3: Description of “made up” products tested	53
Table A.13 — Furniture series 4: Description of “made up” products tested	53
Table A.14 — Furniture series 4 tested in the large room	54
Table A.15 — Furniture series 1 tested in the furniture calorimeter	54
Table A.16 — Furniture calorimeter test series 3	55
Table A.17 — Scenario comparisons	55
Table A.18 — Summary of data	57
Table A.19 — Fire load densities	64
Table A.20 — Calorific values of common fuels	65

Foreword

This Published Document (PD) was published under the Fire Standards Policy Committee. Other parts published or about to be published are as follows:

- *Part 0: Guide to design framework and fire safety engineering procedures;*
- *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 service intervention (Sub-system 5);*
- *Part 6: Evacuation (Sub-system 6);*
- *Part 7: Probabilistic risk assessment.*

These Published Documents are intended to be used in support of BS 7974:2001, *Application of fire safety engineering principles to the design of buildings — Code of practice*.

It has been assumed in the drafting of this PD that the execution of its provisions is entrusted to appropriately qualified and competent people.

Drafting of this publication was completed in July 2001.

Acknowledgement is made to the contribution of Dr D. A. Smith of FRS/BRE in the preparation of this publication.

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 does not of itself confer immunity from legal obligations.

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 69 and a back cover.

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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 a 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. Figure 1 shows the structure of the Code of Practice and the Published Documents.

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.

A fire safety engineering (FSE) approach that takes into account the total fire safety package can often provide a more fundamental and economical solution than more prescriptive approaches to fire safety. It may, in some cases, be the only viable means of achieving a satisfactory standard of fire safety in some large and complex buildings.

Fire safety engineering can have many benefits. The use of BS 7974 will facilitate the practice of fire safety engineering and in particular it will:

- a) provide the designer with a disciplined approach to fire safety design;
- b) allow the safety levels for alternative designs to be compared;
- c) provide a basis for selection of appropriate fire protection systems;
- d) provide opportunities for innovative design;
- e) provide information on the management of fire safety for a building.

Fire is an extremely complex phenomenon and there are still gaps in the available knowledge. When used by suitably qualified persons, experienced in fire safety engineering, this series of documents will provide a means of establishing acceptable levels of fire safety economically and without imposing unnecessary constraints on aspects of building design.

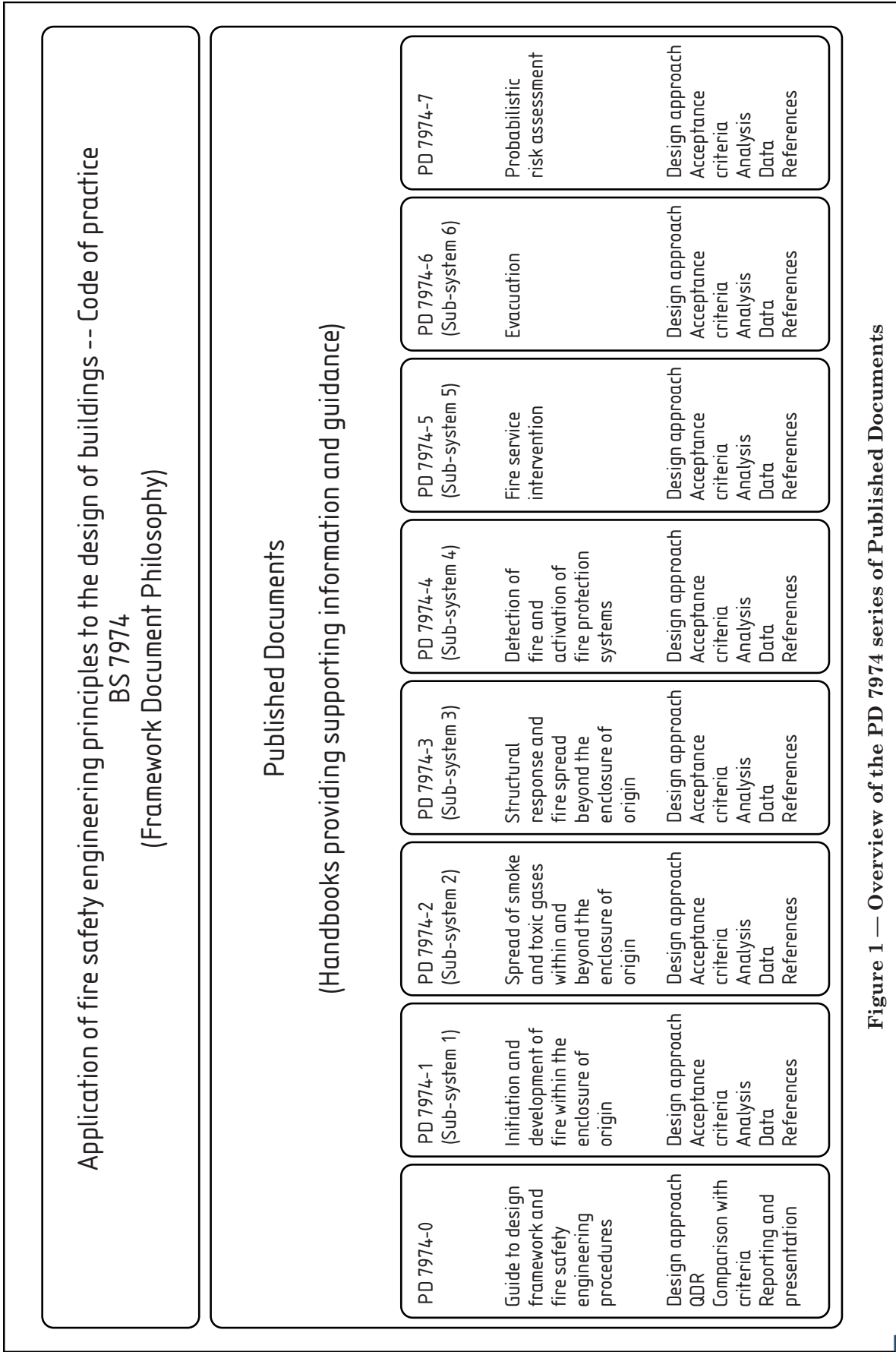


Figure 1 — Overview of the PD 7974 series of Published Documents

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. Guidance is also provided for “special cases” which include malicious fires, racked/stacked storage of goods and fires external to the building.

The characteristics 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 of the design fire from ignition through to decay is used by other Sub-systems as inputs into calculations of events such as time of fire spread from enclosure [PD 7974-3 (Sub-system 3)] and time to activation of suppression systems [PD 7974-4 (Sub-system 4)].

2 Normative references

The following referenced documents are indispensable for the application of this document, For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 476-20, *Fire tests on building materials and structures — Part 20: Method for determination of the fire resistance of elements of construction (general principles)*.

BS 476-21, *Fire tests on building materials and structures — Part 21: Methods for determination of the fire resistance of loadbearing elements of construction*.

BS 476-22, *Fire tests on building materials and structures — Part 22: Methods for determination of the fire resistance of non-loadbearing elements of construction*.

BS 476-33:1993, *Fire tests on building materials and structures — Part 33: Full-scale room test for surface products*.
[ISO 9705:1993]

BS 7974:2001, *Application of fire safety engineering principles to the design of buildings — Code of practice*.

BS EN ISO 13943:2000, *Fire safety — Vocabulary*.

PD 7974-0, *Application of fire safety engineering principles to the design of buildings — Part 0: Guide to design framework and fire safety engineering procedures*.

PD 7974-2 (Sub-system 2), *Application of fire safety engineering principles to the design of buildings — Part 2: Spread of smoke and toxic gases within and beyond the enclosure of origin*.

PD 7974-3 (Sub-system 3), *Application of fire safety engineering principles to the design of buildings — Part 3: Structural response and fire spread beyond the enclosure of origin*.

PD 7974-4 (Sub-system 4), *Application of fire safety engineering principles to the design of buildings — Part 4: Detection of fire and activation of fire protection systems*.

PD 7974-5 (Sub-system 5), *Application of fire safety engineering principles to the design of buildings — Part 5: Fire service intervention*.

PD 7974-6 (Sub-system 6), *Application of fire safety engineering principles to the design of buildings — Part 6: Evacuation*.

3 Terms and definitions

For the purposes of this part of PD 7974, the terms and definitions given in BS EN ISO 13943:2000 and the following apply.

3.1

calorific value

total amount of heat released when a unit quantity of a fuel (measured at 25 °C and atmospheric pressure) is oxidized during its complete combustion in oxygen under specified test conditions

NOTE In a fire, only a proportion of this energy will be released.

3.2

compartment

space defined by fire resisting boundary elements

3.3

critical fire load

fire load required in a compartment to produce a fire of sufficient severity to cause failure of fire resisting barriers or structural elements

3.4

deterministic study

methodology based on physical relationships derived from scientific theories and empirical results, that for a given set of initial conditions will always produce the same outcome

3.5

effective calorific value

moisture corrected value obtained by calculation

3.6

effective fire load density

fire load density within an enclosure or compartment modified by factors that take account of the incomplete combustion of protected fire loads and/or a reduction in the net quantity of heat released resulting from the presence of wet materials

3.7

enclosure

space defined by boundary elements (on all sides) around the point of origin of the fire

3.8

equivalent fire load density

fire load density expressed as an equivalent mass of wood rather than in terms of its calorific value

3.9

fire hazard

source for potential loss of life (or injury) and/or damage to property by fire

3.10

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

3.11

fire load density

fire load divided by the floor area

3.12

fire risk

product of:

- a) probability of occurrence of a fire to be expected in a given technical operation or state in a defined time; and
- b) consequence or extent of damage to be expected on the occurrence of a fire

3.13

fire scenario

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

NOTE It typically defines the ignition and fire growth process, the fully developed stage and the decay stage, together with the building environment and systems that will impact on the course of the fire.

3.14**fire size**

heat release rate of the fire

3.15**flashover**

sudden transition from a localized fire to the ignition of all exposed flammable surfaces within an enclosure

3.16**gross heat of combustion**

energy which unit mass of material or product is capable of releasing by complete combustion, expressed in joules per kilogram

3.17**mixed use building**

building where different parts are used for different purposes

3.18**multiple use building**

part of a building, or a whole building, that is used for different purposes at different times

3.19**probabilistic study**

methodology to determine statistically the probability and outcome of events

3.20**protected fire load**

quantity of combustible material that is unlikely to become fully involved in a fire owing to its being held within containers that have a degree of resistance to fire

NOTE For example, steel filing cabinets.

3.21**smouldering fire**

slow, low-temperature, flameless form of combustion sustained by the heat evolved when oxygen directly attacks the surface of condensed-phase fuel, generally made on increase in temperature and/or by smoke

4 Symbols and abbreviations

A	is the area of the opening (m^2)
A_f	is the total internal floor area (m^2)
A_{fire}	is the area of the fire (m^2)
A_t	is the total surface area of the enclosure (m^2)
A_T	is the area of bounding surfaces (m^2)
A_w	is the area of the ventilation opening (m^2)
c	is the optical density per metre D , or extinction coefficient k , depending on the base used (10 or e) (dimensionless)
C	is the constant for the influences of the properties of the boundary material on the temperature (dimensionless)
c_i	is the gas species mass concentration (kg)
C_p	is the specific heat of air at constant pressure ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)
C_{ps}	is the specific heat capacity of the enclosure boundaries ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)
d_c	is the distance front-to-back of the enclosure (m)
d_r	is the depth of room behind opening (m)
d_s	is the longer linear dimension of the source (m)
D	is the optical density per unit path length of the smoke (m^{-1}) (dB/m)

D_m	is the mass optical density for the fuel concerned ($\text{m}^2 \cdot \text{kg}^{-1}$)
f_b	is the total mass of fuel burnt (kg)
F	is the opening factor ($\text{m}^{1/2}$)
g	is the acceleration due to gravity (m/s^{-2})
h	is the height of the ventilation opening (m)
h_k	is the effective heat transfer coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)
H	is the height of the ceiling above the fire source (m)
ΔH_c	is the heat of combustion of fire load (kJ/kg)
H_c	is the effective heat of combustion (MJ/kg)
H_C	effective calorific value of fire load (kJ/kg)
H_u	is the calorific value of dry material (MJ/kg)
I	is the light intensity a distance s from the observed object of intensity I_0 (dimensionless)
$\frac{I}{I_0}$	is the fraction of light transmitted through smoke (dimensionless)
i	is the species (dimensionless)
K	is the effective emission coefficient (m^{-1})
K_2	is the light extinction coefficient (m^{-1})
k_s	is the thermal conductivity of the enclosure boundaries ($\text{kW} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)
L_f	is the equivalent fire load (kg)
L_t	is the total fire load (kg)
m	is the smouldering pyrolysis rate (g/min^2)
m_c	is the total mass of each combustible material in the enclosure (kg)
m_{CO}	is the mass rate of carbon monoxide production (kg/s)
m_f	is the mass loss rate of fuel (kg/s) or the rate of burning of fuel by mass (kg/s) or the ventilation controlled rate of burning by mass (kg/s)
m_{fo}	is the mass of fuel remaining at flashover (kg)
m_{fuel}	is the rate of burning of fuel by mass (kg/s) or the mass loss rate of fuel (kg/s)
m_{part}	is the mass rate of smoke particle production (kg/s)
m_{pf}	is the fuel controlled pyrolysis/mass loss rate (kg/s)
m_{pfo}	is the peak mass loss rate at flashover (kg/s)
m_r	is the mass remaining at time, t , over burning area (kg)
m_t	is the total mass loss (kg)
M	is the moisture content (% by dry mass)
M_0	is the total initial mass in the burnt area (kg)
q	is the heat release rate to cause a temperature rise (kW)
Q	is the total heat release rate (kW)
$Q(t)$	is the total of heat release rate at time t (kW)
Q''	is the total heat release rate per unit area (kW/m^2)
Q^*	is the dimensionless heat release rate = $\frac{Q}{\rho_a T_a C_p g^{1/2} D_s^{5/2}}$
	or $\frac{Q}{1110D^{5/2}}$ for “normal” ambient conditions when Q is in kilowatts and D in metres
Q_b	is the rate of accumulation of heat in hot gases in the enclosure (kW)
Q_c	is the rate of heat loss by convection through openings (kW)

Q_{control}	is the maximum heat release rate at which the fire can be controlled using suppression (kW)
Q_{enc}	is the rate of heat release in the enclosure (kW)
Q_{fbc}	is the rate of heat release under fuel-bed conditions (kW)
Q_{fo}	is the rate of heat release at flashover (kW)
Q_{max}	is the rate of heat release during the fully developed burning phase (kW)
Q_{p}	is the heat release rate convected by the plume (kW) or the peak heat release rate (kW)
Q_{pf}	is the fuel controlled heat release rate (kW)
Q_{r}	is the rate of heat loss by radiation through openings (kW)
Q_{R}	is the radiative heat flux ($\text{W}\cdot\text{m}^{-2}$)
Q_{steady}	is the rate of heat release during steady burning phase (kW)
Q_{sup}	is the rate of heat release at which suppression activates (kW)
Q_{vc}	is the rate of heat release under ventilation-controlled conditions (kW)
Q_{w}	is the rate of heat loss by radiation and conduction through enclosure construction (kW)
R	is the mass burning rate (kg/s)
RSP	is the rate of smoke production (m^2/s)
S	is the visibility distance (m)
t	is the time from ignition (s)
t_{b}	is the duration of fully developed burning (s)
t_{bo}	is the time to reach burnout (s)
t_{d}	is the time of onset of the decay phase (s)
t_{fo}	is the time to flashover (s)
t_{i}	is the time of ignition (s)
t_{p}	is the thermal penetration time (s)
t_{steady}	is the duration of steady burning (s)
$\bar{T}$	is the mean temperature of the flame (K)
T	is the fire temperature ($^{\circ}\text{C}$)
ΔT	is the temperature rise ($^{\circ}\text{C}$)
$\bar{T}_{\text{f}}$	is the mean furnace temperature ($^{\circ}\text{C}$)
$\bar{T}_{\text{g}}$	is the mean gas temperature ($^{\circ}\text{C}$)
T_{max}	is the maximum exceeded enclosure gas temperature (K)
T_0	is the ambient temperature (K)
THR	is the total heat release rate (MJ)
TSP	is the total smoke production (m)
V	is the volume flow rate of smoke (m^3/s)
V_{f}	is the volume flow rate of smoke at a location (m^3/s)
V_{t}	is the total volume of smoke at a location (m^3)
w	is the width of wall containing the opening (m)
w_{c}	is the width of the wall containing ventilation openings (m)
Y_{i}	is the mass yield of chemical species (kg) or the mass yield of species i (dimensionless)
z_{fl}	is the mean height of luminous flames above the fuel surface (m)
α	is the fire growth parameter (kJ/s)
δ	is the thickness of the enclosure boundaries (m)
ϵ_{f}	is the emissivity of the flame (dimensionless)
ϵ_{smoke}	is the smoke mass conversion factor ($\text{kg}/\cdot\text{kg}$)

θ	is the temperature rise above ambient in the upper gas layer (°C)
λ_f	is the thickness of the flame (m)
ρ	is the density of the enclosure boundaries (kg·m ³)
ρ_0	is the ambient air density (kg/m ³)
σ	is the Stefan-Boltzmann constant (5.67×10^{-11} W·m ⁻² ·K ⁻⁴)
ϕ	is the configuration factor (dimensionless)
χ	is the fraction of the total heat release rate convected by the plume (dimensionless)

5 Design approach

5.1 Experience and qualifications

The complexity of the interactions between people, buildings and fire is such that no single set of calculation procedures can be applied to all types of building in all circumstances. Therefore FSE requires a greater degree of care and responsibility by the designer than does the application of prescriptive codes. It is essential that the application of FSE be entrusted to suitably qualified and experienced personnel. In assessing the suitability of FSE design personnel, professional qualifications (e.g. Chartered Membership of the Institution of Fire Engineers) and experience on projects of similar complexity should be taken into account.

5.2 Framework

A framework of the application of engineering approaches to fire safety in buildings is provided in BS 7974. PD 7974-0 provides additional guidance to assist the fire safety engineer through the design process.

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 fire engineering evaluation of a building. A representation of the concept is shown in Figure 2. Some of the potential interactions between Sub-systems are illustrated. The parameters are often both inputs into one particular Sub-system and outputs from another.

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 data and calculation methods are not precluded and might be required. Satisfactory justification of any calculation method or approach selected should always be provided.

With reference to Figure 2, this Published Document provides information on the initiation and growth of a fire (within the enclosure of origin). This process requires information from the qualitative design review (QDR) process on:

- building characteristics:
 - dimensions, nature and geometry of construction.
- enclosure:
 - wall/ceiling linings, ventilation systems, unusual fire hazards, potential ignition sources.
- fire load:
 - type, location, arrangements and quantity of combustibles.
- environmental influences (internal):
 - temperature;
 - air movement.

See PD 7974-0 for additional detailed guidance and information.

Given this information, it is then possible to calculate a number of parameters, which include:

- heat release rate;
- mass production rate of smoke;
- mass production rate of fire effluents (e.g. CO);
- flame size and temperature;
- temperature within enclosure;
- time to flashover;
- area of fire involvement.

These parameters are the primary outputs from Sub-system 1 required by the other Sub-systems.

The calculation methods for the above parameters assume that the fire grows unimpeded by active fire protection measures such as suppression systems, smoke heat and exhaust ventilation systems (SHEVs) and fire barriers and without human interaction such as fire brigade or building occupants. Therefore it should be remembered that the listed parameters might be modified by information from other Sub-systems, in particular Sub-systems 4, 5 and 6 (PD 7974-4, PD 7974-5 and PD 7974-6).

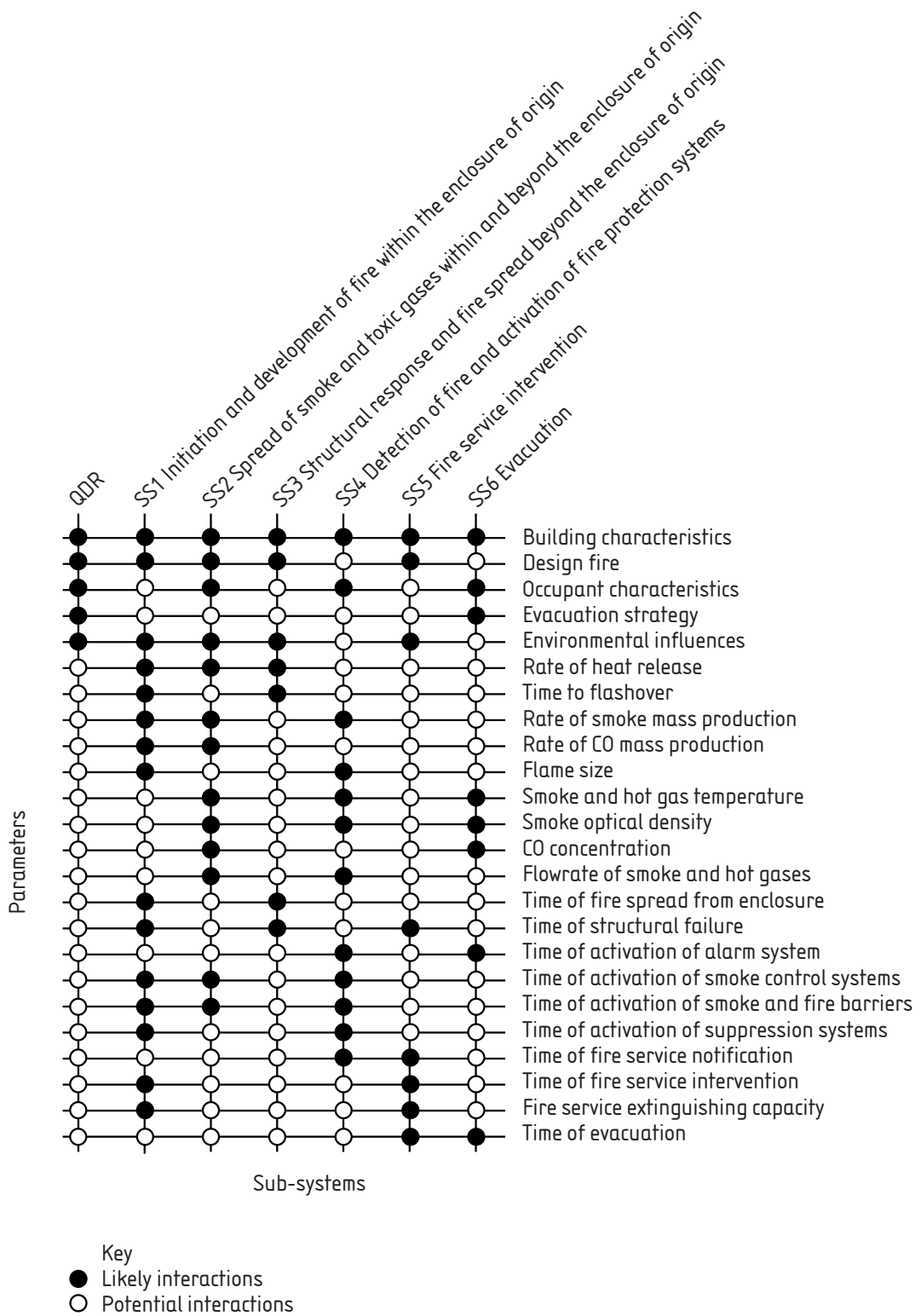
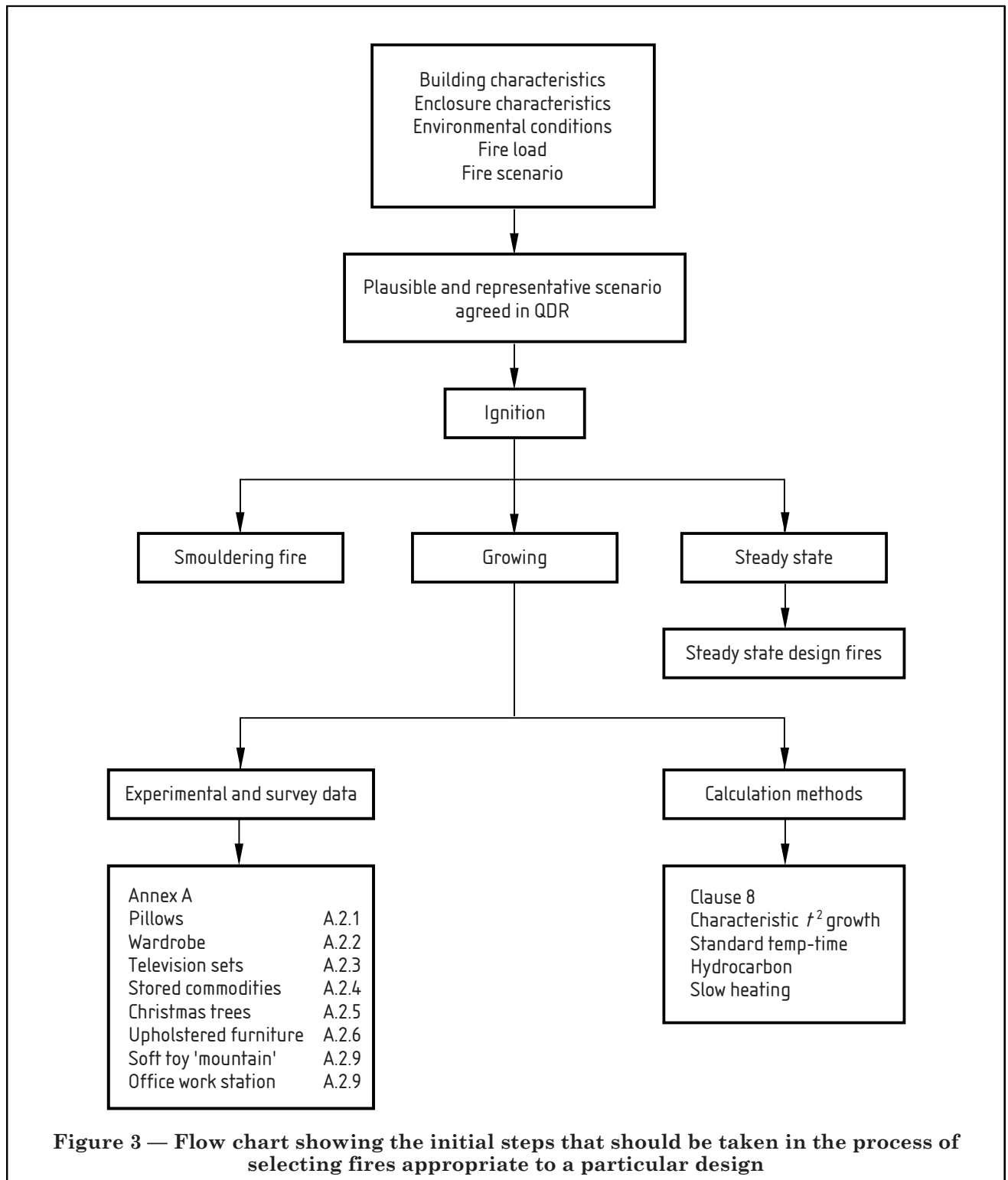


Figure 2 — Sub-system interactions



5.3 Design fires

The characteristics of a 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 design fire may be characterized in terms of:

- heat release rate;
- toxic species production rate;
- smoke production rate;
- fire size;
- fire duration;
- time to key events e.g. flashover.

The design fire should be based on the materials within an occupancy. However, while the heat release rates for many materials are known, it is rarely possible to say that a fire will consist of a known quantity of material. Within an occupancy, a fire will involve a combination of different materials so that the heat release rate for a particular occupancy will be a function of all the materials present. The likely size of a fire can be deduced from the analysis of statistics of fires in the type of occupancy of interest or from experiments on approximately representative fuel arrays.

A design fire can either be a steady state fire with a constant heat output or a time-dependant growing fire (see Clause 8). A growing fire is assumed when assessing the time to key events such as flashover, operation of detectors, or loss of tenability.

The assumption of a steady state fire allows the smoke control system to cater for all fires up to design fire size and by not considering the growth phase of the fire, can introduce a significant margin of safety into the system design.

5.4 Building characteristics

Information on building characteristics will be provided from the QDR and consideration in terms of the potential consequences should be given to the factors influencing the fire growth process which include:

- a) building:
 - 1) dimensions of construction/building;
 - 2) geometry of construction/building;
 - 3) nature of construction of building (materials and method).
- b) enclosure:
 - 1) wall and ceiling linings;
 - 2) ventilation conditions (natural and/or mechanical);
 - 3) unusual fire hazards;
 - 4) potential ignition sources.

5.5 Fuel load

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 process which include:

- a) type of combustibles;
- b) quantity of combustibles;
- c) location of combustibles;
- d) arrangement of combustibles.

5.6 Environmental influences

Information on environmental influences will be provided from the QDR and consideration, in terms of the potential consequences, should be given to all relevant influences on the fire growth process which include:

- a) internal ambient temperatures;
- b) internal ambient air movement.

5.7 Fire load

5.7.1 General

Fire load data are required for the evaluation of structural failure and fire spread beyond the enclosure of origin (Sub-system 3).

A fire load can be composed of:

- a) permanent fire loads (combustible materials including load bearing structure, linings, finishes);
- b) variable fire loads (combustible materials which vary during the life of the building);
- c) protected fire loads (combustible materials protected against exposure to fire i.e. low probability of involvement in the fire);
- d) unprotected fire loads (combustible materials not protected).

If it is assumed that all the fire loads in a building design are unprotected, a conservative evaluation will result.

5.7.2 Fire load density

The fire load can be assessed according to the use of the specific building. Alternatively generalized data from surveys of similar building uses can be assumed. For generalized data it is suggested that a minimum of five representative buildings, or parts of buildings, are surveyed to determine the masses of combustible materials within an enclosure. These are then converted to the fire load density for the enclosure using;

$$q_k = \sum \frac{m_c H_c}{A_f}$$

where

- q_k fire load density for the enclosure (MJ/m²)
- m_c total mass of each combustible material in the enclosure (kg)
- H_c effective calorific value of each combustible material (MJ/kg)
- A_f total internal floor area of the enclosure (m²)

The effective calorific value of a combustible material can be calculated by:

$$H_c = H_u(1 - 0.001M) - 0.025M$$

where

- H_u calorific value of dry material (MJ/kg)
- M moisture content (% by dry mass)

There are significant numbers of fire load density data that have been published. A table of fire load densities is provided in Annex A. This data was taken from the CIB W14 Workshop report [1], which dates back to 1983. When using published data, the fire safety engineer should ensure that the country of origin is relevant to design application and that trends in lifestyles do not mean that the data is out-dated and therefore inappropriate. In the UK, it is recommended that the 80 % fractile value be taken as the fire load density for design. This is the average value that is not exceeded in 80 % of rooms or occupancies. Local concentrations of fire load can exceed this value.

5.8 Time to flashover

The design objectives for a project are often linked to the time to key events. One such key event is the time to flashover. The evaluation of time to flashover necessitates a transient approach to fire safety design. 8.2.1.9 of this Sub-system includes several quantitative methods for determining the heat release rate at flashover. Given the heat release rate that results in flashover for a specific compartment, the time to flashover can be found by reference to the appropriate fire growth curve. The calculation process is represented schematically in Figure 4.

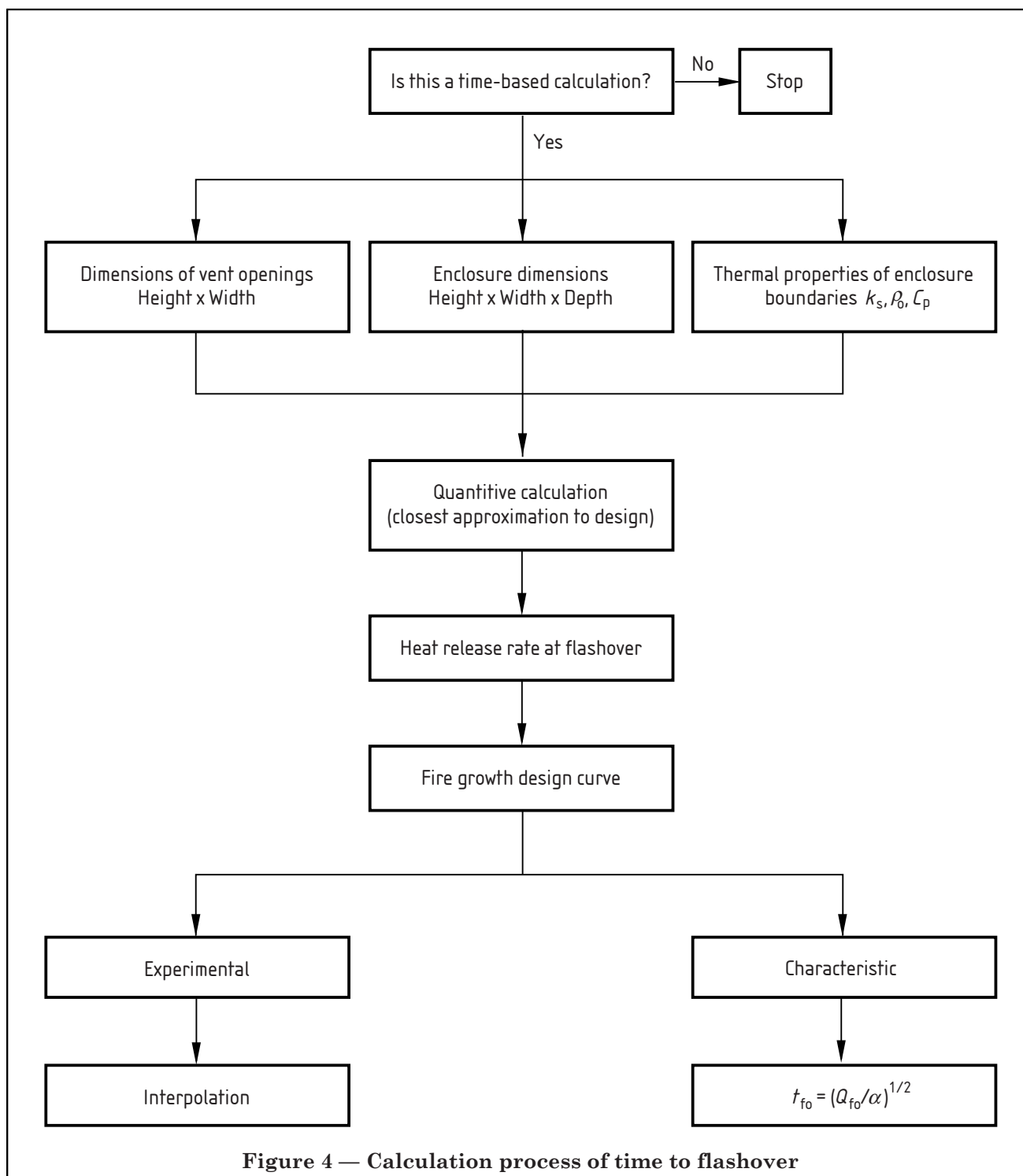


Figure 4 — Calculation process of time to flashover

5.9 Sensitivity analysis

The design fire characteristics calculated in Sub-system 1 will have a major impact upon many aspects of the design since they form the inputs into many of the deterministic quantitative design calculations carried out in the other Sub-systems. It might be possible to deal with the uncertainties associated with the deterministic design by taking a conservative approach. However, the judgement of conservatism is very subjective. A worst case design fire in terms of maximum size or growth rate will typically also be the worst case for:

- effect of smoke control system;
- effect of suppression systems on fire growth;
- time to structural failure;
- time of fire spread from enclosure;
- fire service extinguishing capacity.

However, the same design fire can represent the best case test for:

- time of activation of alarm system;
- time of activation of smoke control systems;
- time of activation of smoke and fire barriers;
- time of activation of suppression systems.

It is therefore recommended that a sensitivity study be carried out on the consequences of the choice of design fire on the different parts of the quantitative assessment.

The objective of a sensitivity study 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.

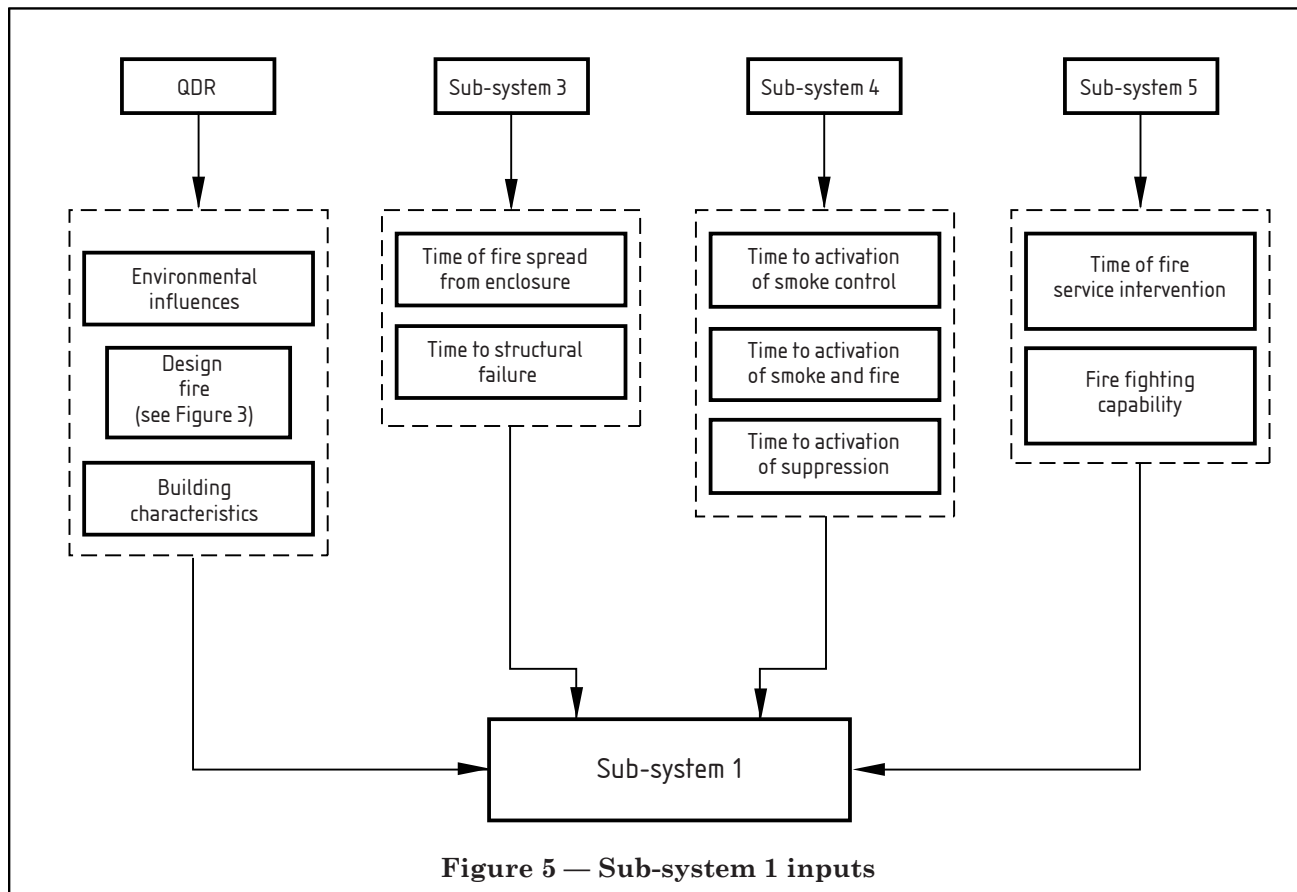
If a single assumption is shown to be critical to the design and potentially the level of safety, consideration should be given to providing a degree of redundancy in the design or to carrying out a probabilistic study.

Table 1 — Checklist of factors to be considered when defining a design fire

	Factors to be considered
Building characteristics	Dimensions of building Geometry of building Nature of construction of building (materials and method)
Enclosure characteristics	Wall and ceiling linings Ventilation conditions (natural or mechanical) Thermal properties of enclosure boundaries
Environmental conditions	Ambient temperature conditions Ambient air movement
Fire load	Fuel type Fuel quantity Fuel location Fuel arrangement Wall and linings
Fire scenario	Ignition sources Ignition location Fuel involved in ignition Type of fire growth Unusual fire hazards Events influencing fire growth e.g. window breakage

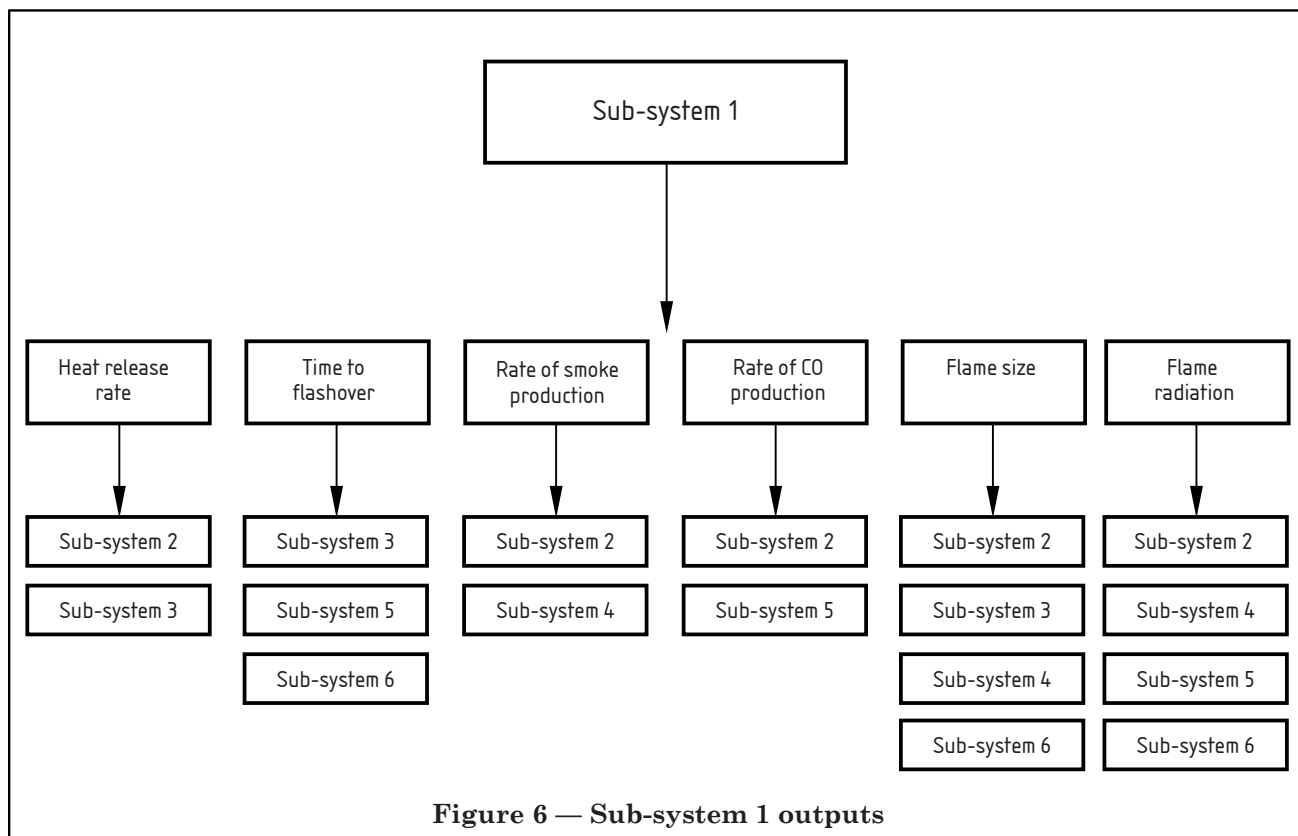
6 Inputs

The inputs given in Sub-system 1 are illustrated in Figure 5.



7 Outputs

The outputs given in Sub-system 1 are illustrated in Figure 6.



8 Analysis

8.1 Classification

8.1.1 General

Fire growth can be quantified according to the following stages (see Figure 8 for example):

- ignition;
- pre-flashover;
- flashover;
- fully-developed fire;
- decay.

It should be noted that flashover does not necessarily occur.