PUBLISHED DOCUMENT

PD 7974-2:2002

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 (Sub-system 2)

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Contents

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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 1: Initiation and development of fire within the enclosure of origin;*
- — *Part 3: Structural response and fire spread beyond the enclosure of origin;*
- — *Part 4: Detection of fire and activation of fire protection systems;*
- — *Part 5: Fire service intervention;*
- — *Part 6: Evacuation;*
- — *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 and Prof G. Cox, both 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.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 46, an inside back cover 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.

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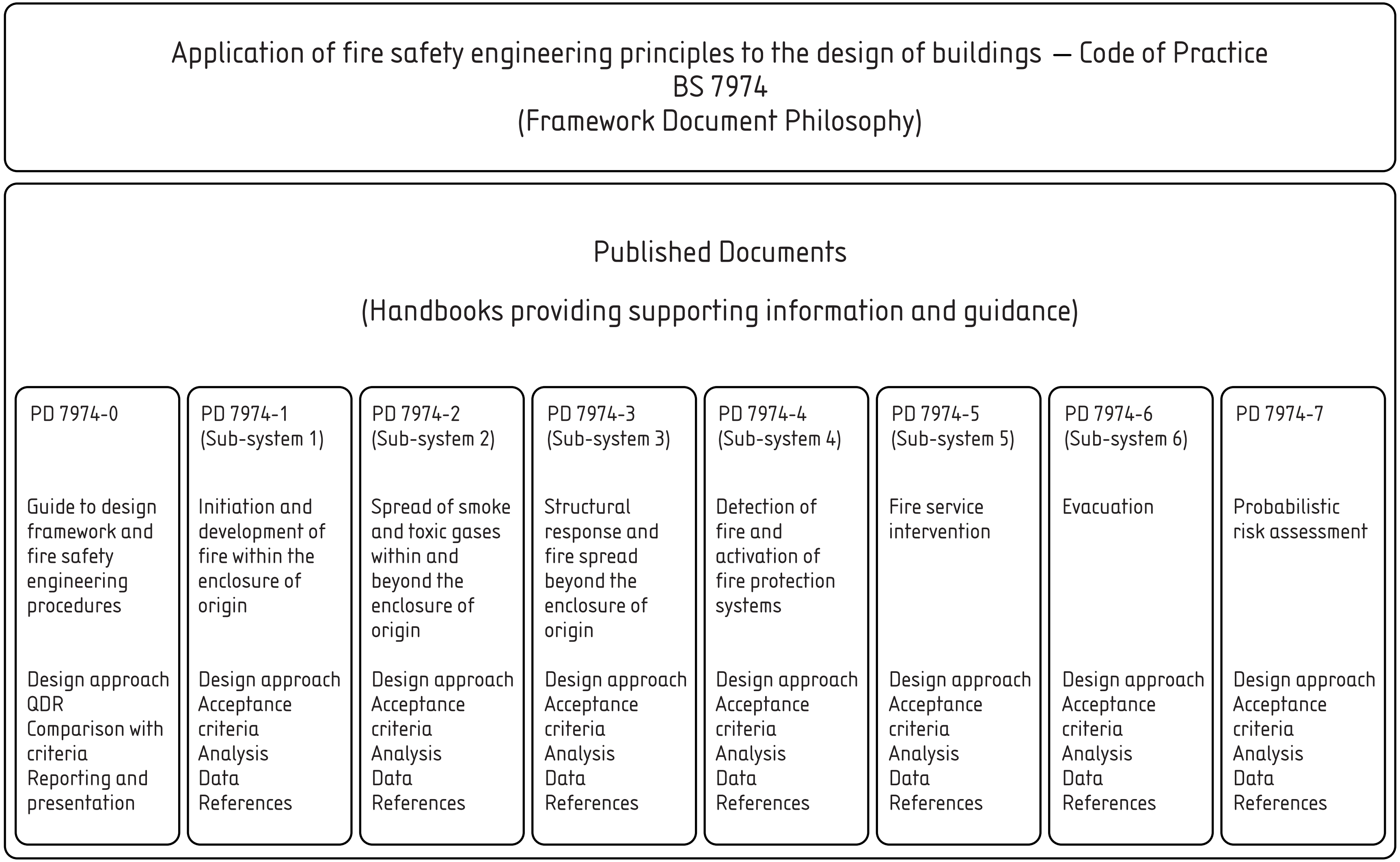

Figure 1 — BS 7974 and the Published Documents

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1 Scope

This Published Document provides guidance on the application of fire safety engineering principles for the treatment of smoke movement, control and management problems. The guidance is intended primarily for professional engineers with a responsibility for the design or assessment of fire safety in buildings.

Sub-system 1 (PD 7974-1) provides information on the rate of production of heat and combustion products from the fire source. The aim of Sub-system 2 is to provide design approaches to estimate the spread of the combustion gases within and beyond the room of origin and to evaluate their properties, i.e. temperature, visibility and concentration of toxic products. This information can be used to calculate the time between the detection of a fire to conditions developing which would be dangerous to building occupants. This will enable the design of fire safety measures to ensure that sufficient time is available for escape. It also provides information that will allow property issues to be assessed.

This Published Document forms part of a series of Sub-systems 1 to 6 (PD 7974-1 to PD 7974-6), but may, in consultation with the appropriate references, be regarded as "stand-alone" guidance.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of this Published Document. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 476-31.1:1989*, Methods for measuring smoke penetration through doorsets and shutter assemblies.*

BS 5588-4:1998, *Fire precautions in the design, construction and use of buildings — Code of practice for smoke control using pressure differentials.*

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

DD 240:1997, *Fire safety engineering in buildings — Part 1: Guide to the application of fire safety engineering principles.*

ISO DIS 13943:2000, *Fire safety — Vocabulary.*

ISO/TR 13387-1:1999, *Fire safety engineering — Part 1: Application of fire performance concepts to design objectives.*

ISO/TR 13387-2:1999, *Fire safety engineering — Part 2: Design fire scenarios and design fires.*

ISO/TR 13387-3:1999, *Fire safety engineering — Part 3: Assessment and verification of mathematical fire models.*

ISO/TR 13387-4:1999, *Fire safety engineering — Part 4: Initiation and development of fire and generation of fire effluents.*

ISO/TR 13387-5:1999, *Fire safety engineering — Part 5: Movement of fire effluents.*

ISO/TR 13387-6:1999, *Fire safety engineering — Part 6: Structural response and fire spread beyond the enclosure of origin.*

ISO/TR 13387-6:1999, *Fire safety engineering — Part 7: Detection, activation and suppression.*

ISO/TR 13387-8:1999, *Fire safety engineering — Part 8: Life safety-occupant behaviour, location and condition.*

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 7974-1, *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).

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

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

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

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

3 Terms and definitions

For the purpose of this part of PD 7974, the following terms and definitions apply.

3.1
ambient condition
property of the surroundings outside the influence of a fire

3.2
air entrainment
mixing of ambient air into a jet or plume of gas or liquid as a result of momentum transfer

3.3
axi-symmetric plume
plume of combustion products and entrained air rising above a fire source where the air is entrained symmetrically towards the source

3.4
backdraught
explosive or rapid burning of unburnt pyrolysis products that occurs when oxygen is introduced into a building that has not been properly ventilated and has a depleted supply of oxygen due to fire

3.5
ceiling jet
flow of hot fire gases driven away from the smoke plume ceiling impingement point

3.6
channelling screen
smoke barrier installed beneath a balcony or projecting canopy to direct the flow of smoke and hot gases from a room opening to the spill edge

3.7
compartment
space defined by fire resisting boundary elements

3.8
Computational fluid dynamics model
CFD model
field model

computer simulation model where the fundamental equations of heat and mass transfer are solved using numerical methods

NOTE In contrast to zone models, computers provide the enabling technology for these models.

3.9
convective heat flux
heat flux carried by the convected motion of the fire gases

3.10
design fire
hypothetical fire that is agreed as representative of actual severe fires likely to occur in a particular fire scenario

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3.11
discharge coefficient
ratio of actual flow rate, measured under specified conditions, to the theoretical flow rate through an opening

NOTE For example, a vent.

3.12
discretize
process of replacing a continuous mathematical function by its numerical counterpart where it has a value at only discrete intervals

NOTE For example, grid points in a numerical mesh.

3.13
enclosure
space defined by boundary elements (on all sides) around the point of origin of the fire

3.14
escape time
sum of pre-movement time and travel time to and through an exit to a place of safety

3.15
fire scenario
set of circumstances, chosen as an example, that defines the development of fire and the spread of combustion products throughout a building or part of a building

3.16
flashover
rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure

3.17
fire detection and alarm
detection of a fire by occupants and/or mechanical device and visual, audible or some other method of alerting the occupants

3.18
fire safety engineering
use of engineering principles for the achievement of fire safety

3.19
free-hanging smoke curtain
smoke curtain fixed only along its top edge

3.20
iteration
repeated calculation performed on discretized equations

NOTE These are normally performed by taking the solution from one calculation, the previous iteration, as an input to the next iteration. This process is repeated many times over until the differences between successive iterations are acceptably small.

3.21
natural ventilation
ventilation resulting from the exploitation of the thermal buoyancy of the smoky gases to exhaust them to be replaced at inlets by ambient air

3.22
powered smoke and heat exhaust ventilation
ventilation resulting from the application of externally powered ventilators (e.g. fans) to exhaust smoky gases to be replaced at inlets by ambient air

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3.23

place of safety

predetermined place in which persons are in no danger from the effects of fire

3.24

pre-movement time

interval between the time at which a warning of fire is given and the time at which the first move is made towards an exit

3.25

sensitivity analysis

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

3.26

smoke curtain

curtain to restrict the spread of smoke and hot gases from a fire

NOTE It often forms part of the boundary of a smoke reservoir.

3.27

smoke explosion

explosion of a mixture of flammable fire gases (pyrolized fuel and partial combustion products) and air

NOTE A particular case of a backdraught.

3.28

replacement air

ambient air replacing the mass flow of smoky gases vented to the external environment

3.29

smoke reservoir

region within a building or other construction work limited or bordered by smoke curtains or structural elements so as to retain a thermally buoyant smoke layer in the event of a fire

3.30

spill plume

vertically rising plume resulting from the an initially horizontally-flowing smoke layer encountering a free edge

3.31

steady state design

design solutions which are time invariant, i.e. hot gas layer depth and temperature remain constant over time

NOTE These are usually based upon the design fire burning steadily at its largest size.

3.32

time dependent design

design solutions based upon time-dependent input parameters

NOTE Usually these are designed to maintain safe conditions for a specific time, e.g. time required for people to reach a place of safety.

3.33

travel distance

actual distance to be travelled by a person along an escape route to the nearest exit to a place of safety or a refuge or a protected escape route, having regard to the layout of walls, partitions and fittings

3.34

virtual origin

point or line from which a plume appears to have emerged

NOTE It can be above or below the real fire source depending on its buoyancy and momentum.

3.35

visibility

ability to see through smoke

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3.36

zone model

theoretical simulation of the whole system characterizing the enclosure fire by a series of relatively few separable component processes. Each component is represented by an equation or estimation formula

3.37 Nomenclature

α	is an entrainment coefficient (dimensionless);
κ	$= \left(\frac{2}{3}\frac{\rho_0}{T}\sqrt{2g\theta\ T_0 \cdot \kappa_m}\right)$ ($kg \cdot s^{-1} \cdot m^{-5/2}$);
κ_m	is a “profile correction factor” (dimensionless);
ρ_0	is the ambient air density (kg/m^3);
ρ_α	is the density of the species α (kg/m^3);
ρ_c	is the density of the boundary surface;
θ	is an excess temperature (°C);
θ_c	is the maximum temperature rise in the ceiling jet (°C);
θ_{imp}	is the maximum temperature rise in the vertical plume at the impingement point (C);
θ_1	is the excess temperature of the smoke layer (°C);
θ_{max}	is the maximum temperature rise in the ceiling jet (C);
χ	is the fraction of the total heat release convected by the plume (dimensionless);
A_i	is the total area of all inlets (m^2);
A_v	is the throat area of the ventilator (m^2);
b	is the horizontal distance from the opening to balcony edge (m);
c_α	is the mass concentration of species a (kg/m^3);
C_d	is a discharge coefficient for the opening (dimensionless);
C_e	is the constant of proportionality in equation (8) or equation (18) ($kg/s \cdot m^{5/2}$);
C_i	is the entry coefficient for inlets (dimensionless);
C_p	is the specific heat of air at constant pressure ($kJ/kg \cdot K$);
C_v	is the coefficient of discharge (dimensionless);
C_w	is the specific heat of the bounding solid;
C_α	is the volume concentration of species α (dimensionless);
d_s	is the longer linear dimension of the source (m);
d	is the smoke layer depth (m);
D	is the optical density per unit path length of the smoke (m^{-1});
D_c	is the deflection of the curtain (m);
D_m	is the mass optical density for the fuel concerned (m^2/kg);
D_s	is the source diameter or characteristic length (m);
f_b	is the total mass of fuel burnt (kg);
g	is the acceleration due to gravity (m/s^2);
h	is the height of opening (m);
H	is the height of the ceiling above the fire source (m);
I/I_0	is the fraction of light transmitted through smoke (dimensionless);
k_w	is the thermal conductivity of the bounding solid ($kW/m \cdot K$);

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K is light extinction coefficient (m^{-1});
l is the corridor half width (m);
L is the lateral extent of the spill plume (m);
L_c is the length of the smoke curtain measured along the fabric (m);
m is the mass flow rate entering the layer (kg/s);
m_{air} is the mass flow rate of air entrained (kg/s);
m_{fuel} is the mass burning rate of fuel (kg/s);
m_{smoke} is the mass flow rate of smoke (kg/s);
m_b is the mass flow rate of smoke approaching a balcony edge (kg/s);
m_{crit} is the critical mass flow rate of an exhaust point prior to plug-holing (kg/s);
M_b is the weight per unit length of the curtain's bottom bar (kg/m);
M_c is the weight per unit area of the curtain fabric (kg/m^2);
n is a constant in equation (28) (dimensionless);
N is the number of extract vents (dimensionless);
p is the perimeter of the source (m);
Q_p is the rate of heat release convected by the plume (kW);
Q is the total rate of heat release of the fire source (kW);
Q'' is the total rate of heat release per unit area of fire source (kW/m^2);
$Q^* = \dfrac{Q}{\rho_a T_a C_p g^{1/2} D_s^{5/2}} = \dfrac{Q}{1\,110 D^{5/2}}$ for "normal" ambient conditions when Q is in kW and D in metres (dimensionless);
r is the radial distance from the ceiling impingement point (m);
s is optical path length (m);
S is the visibility distance (m);
t is the thermal penetration time (s);
T is the local smoke temperature (K);
T_0 is the ambient air temperature (K);
u_{max} is the maximum gas velocity in the ceiling jet (m/s);
V is the volume flow rate of smoke (m^3/s);
V_t is the total volume of smoke at a location (m^3);
w is the width of the opening on to the balcony (m);
w_V is the characteristic width of the ventilator (m);
y is the distance along the corridor from the impingement point (m);
Y_α is the mass yield the species α (kg/kg)-the ratio of mass generation rate of the species, α, to mass gasification rate of the fuel;
Y_{fu} is the local mass fraction of fuel (dimensionless);
Y_{ox} is the local mass fraction of air (dimensionless);
z is height above the fuel surface or balcony edge (m);
z_0 is the height of the virtual source above the fuel surface (m);
z_{fl} is the mean height of luminous flames above the fuel surface (m);
z_{max} is the maximum height of rise of smoke plume (m).

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4 Design approach

4.1 Objective of Published Document

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 1. 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.

This Published Document provides guidance on the application of fire safety engineering principles for the treatment of smoke movement, control and management problems. The guidance is intended primarily for professional engineers with a responsibility for the design or assessment of fire safety in buildings.

Sub-system 1 (PD 7974-1) provides information on the rate of production of heat and combustion products from the fire source. The aim of Sub-system 2 is to provide design approaches to estimate the spread of the combustion gases within and beyond the room of origin and to evaluate their properties, i.e. temperature, visibility and concentration of toxic products. This information can be used to calculate time to danger from the detection of a fire and to design any fire safety measures required to ensure that sufficient time is available for escape.

It is recommended that a sensitivity analysis be conducted to examine the consequences of the choices made for smoke control and for design fire on the rigour of the solution proposed. The objective of the analysis is to establish the impact on the output parameters caused by variation of the input parameters. If a particular choice is shown to be critical to the design, consideration should be given to providing a degree of redundancy to the design.

It is important to appreciate that what may be conservative for one component of the design may be a best case for another. A large or fast growing design fire can, for example, be conservative for estimation of smoke exhaust capacities but would be overly optimistic for fire detection or suppression activation times.

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 may be required. Satisfactory justification of any calculation method or approach selected should always be provided.

This Published Document forms part of a series of Sub-systems 1 to 6 (PD 7974-1 to PD 7974-6), but can, in consultation with the appropriate references, be regarded as “stand-alone” guidance. Guidance is also available from other Published Documents including the ISO/TR 13387 series and references [1] to [5].

4.2 Qualifications of the user

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 buildings in all circumstances. Therefore fire safety engineering 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 fire safety engineering be conducted by suitably qualified and experienced personnel. In assessing the suitability of fire safety engineering design personnel, professional qualifications (e.g. Chartered Membership of the Institution of Fire Engineers), knowledge of current engineering guidance and handbooks and experience on complex projects should be taken into account.

4.3 The hazard associated with smoke

Smoke is the term used to describe the “airborne” products of combustion from the fire together with large volumes of air that become entrained into them due to their motion. These combustion products can contain solid and liquid particulates within a gaseous mass.

Almost all fires produce smoke which when enclosed by a building has the potential to become extremely hazardous to its occupants and damaging to property. Most deaths in fires are due to smoke inhalation rather than to the victim having been burned.

The gaseous combustion products, chiefly carbon dioxide and water usually include toxic gases, the most common being carbon monoxide, although hydrogen cyanide and other minor species might be present to some extent. Amongst these, irritant gases such as acrolein can have a significant effect on people attempting to escape fire.

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The solid and liquid fractions of the products of combustion are responsible for the poor visibility through smoke. This adds to the problems presented by the smoke. Not only is it physiologically hazardous in its own right but escape through it is made more difficult by it obscuring escape routes. These fractions can themselves be irritants, and can be particularly dangerous to people who are subject to asthma or other respiratory problems.

The reduction in oxygen due to combustion can itself be dangerous in some situations and can result in the suffocation of victims trapped in smoke. The heat of the combustion products is also potentially hazardous to the building occupants, either through their potential immersion in the smoke or by thermal radiation from the hot smoke layer.

Smoke can also cause damage to property. Most fires produce soot and many generate corrosive gases such as hydrogen chloride. The effect of these on sensitive equipment can be responsible for large monetary losses due to equipment damage, the need for system clean-up and consequent business interruption.

There are also hazards that have been termed “smoke explosions” associated with smoke containing the unburnt pyrolysis products of fire. These hazards are more properly considered within the broader category of backdraught that can occur as a result of the sudden availability of fresh air.

All fires start small and grow, some only smoulder. In the earliest stages when detection is the priority, the fire will not yet be controlling the airflow patterns. At this time the smoke is simply a “passenger” on the prevailing natural air currents caused by space heating, wind pressures etc. Most of what follows describes the processes after the fire has become large enough for buoyancy to dominate these currents. The treatment of these very early conditions is not covered here except in the section on CFD modelling which does encompass both situations.

4.4 Smoke dynamics

It is important to understand the basic mechanisms that control the growth of fire in an enclosure.

a) The fire starts for whatever reason, its rate of growth depending upon the materials involved, their orientation and positions relative to each other. In most situations there is sufficient oxygen to support combustion in the first few minutes and the fire growth and smoke production are controlled by the fuel.

b) Because of its buoyancy the smoke rises from the fire. Initially the buoyancy is low and the smoke will follow the ambient air currents present before the fire occurred but as its heat release increases, its buoyancy increases and it soon begins to dominate air currents in the enclosure. When the fire reaches a sufficient size the smoke rises in a plume towards the ceiling. As it does so it entrains large volumes of air greatly increasing smoke volume but reducing its temperature and concentrations of chemical constituents.

c) The total entrained volume increases substantially with increasing height of rise of the plume. With sufficient buoyancy the smoke eventually impinges the ceiling, spreading out radially to reach any side-walls and then to begin to form a layer which deepens as more smoke is produced.

d) Smoke eventually flows out into adjacent spaces through any high level openings. This outflow is balanced by an inflow of air usually at low level. The openings may be by design or by failure of, for example, a glass partition.

e) As new flammable material becomes involved as a result of increasing heat transfer to it, more air is required for the fuel volatiles to burn. If this is not available the fire will either not grow any further or the fuel volatiles will instead burn outside the enclosure of origin in the open air or in an adjacent space. This is particularly likely after flashover when a sudden dramatic growth in the fire occurs as a result of the simultaneous involvement of all flammable material in the enclosure.

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5 Smoke control

5.1 Design objectives

5.1.1 *General*

Since smoke control can have a major impact on the overall design of the building it needs to be considered at the earliest possible stage of the design process. Indeed where it is used to allow increased means-of-escape travel distances it will have a profound effect on the overall concept.

Smoke control systems are usually designed to maintain a tenable environment for occupants to enable their safe escape from the building or to a place of refuge. They can also be required to assist in property protection; to assist the entry and subsequent operations of fire-fighters; and, by limiting the temperature of the smoke layer, assisting the fire performance of the structure.

Smoke control systems are required both for protection of the enclosure of fire origin as well as preventing smoke spread to adjoining spaces. These two requirements may need to be satisfied by different types of system.

It will be for the QDR to determine where these different treatments should be applied and to ensure their compatibility. References [4] and [5] (CIBSE Guide E Fire Engineering, Chapter 7 *Fire and Smoke ventilation* and BRE 368) provide additional guidance to assist the decision-making process.

There are very few cases where Codes of Practice require smoke control measures. Approved Document B [6] specifies that new shopping malls in England and Wales conform to BS 5588-10, which specifies use of smoke control in those premises. Smoke control is also required for basements (for fire fighting) and service corridors in shopping malls although it is becoming common in large department stores as well. The only other scenario where smoke control is mandatory is atrium buildings that are over 30 m high (BS 5588-7), although it is a permitted alternative in other scenarios.

The four main objectives for the smoke control systems are given in **5.1.2**, **5.1.3**, **5.1.4** and **5.1.5**.

5.1.2 *Protection of means of escape*

The objective is to achieve a desired smoke free clear layer beneath a smoke layer. This approach is commonly used where the purpose of the smoke exhaust ventilation system is to allow the continued use of escape routes which are in the same space as the fire (examples include enclosed shopping malls and many atria or large single storey spaces e.g. for public assembly). The thermally buoyant smoke forms a layer beneath the ceiling. The smoke exhaust (using either natural smoke exhaust ventilators or powered smoke exhaust ventilators) is calculated to be large enough to keep the smoke at a safe height above the heads of people long enough for them to make their safe escape. It is essential that the system comes into operation as early as possible during the fire, and it is usual to initiate operation automatically on receipt of a signal from a smoke detection system.

Smoke control using pressure differentials is a different technique often used to protect stairwells and sometimes corridors against the ingress of smoke. The use of smoke control doors in conjunction with a well-sealed corridor or stairway construction can also resist smoke ingress onto protected routes.

5.1.3 *Temperature control*

Smoke and heat exhaust ventilation systems can be designed to minimize the temperature of the gases in the buoyant layer in critical areas of the design. This protects the use of materials that would otherwise be damaged by the hot gases. A typical example is where an atrium facade has glazing which is not fire resisting, but which is known to be able to survive gas temperature gradients up to some specified value. The use of a “temperature control” smoke exhaust ventilation system in such a case could, for example, allow the adoption of a phased evacuation strategy from higher storeys separated from the atrium only by such glazing.

5.1.4 *To assist fire fighting operations*

In extensive and multi-storey complex buildings fire-fighting and rescue operations can be severely hampered by the presence of hot smoky gases. The travel time from the fire appliances to upper and lower levels can be improved by the provision of smoke control systems installed primarily for the occupants’ means of escape or protection of property.

Smoke control systems can also be installed for fire-fighting alone and here the design criteria will be different reflecting the specialist equipment clothing and training of the fire service.

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5.1.5 *Property protection*

Smoke control systems can be used to protect not only the contents of a building but also some aspects of the structure. Heat can be vented by the smoke exhaust system to ensure that the heat flux to critical structural elements is kept below acceptable criteria. Such smoke control systems usually depend on the inclusion of measures to limit fire size.

Depending on the materials present, a property protection philosophy can be based on the need to maintain the hot buoyant smoke layer above sensitive materials, or can be based on the need to maintain the smoke layer below a critical temperature.

5.2 Smoke control techniques in common use

5.2.1 *Smoke containment*

Smoke containment relies on physical barriers to limit the spread of smoky gases from one space in a building to another space. Passive compartmentation such as doors, shutters, walls and floors, can provide some protection against smoke penetration. The extent to which smoke leaks through these barriers depends on the size and shape of leakage paths and the pressure differentials across them.

These leakage paths can be eliminated, or substantially reduced by the incorporation of linear gap sealing systems, penetration sealing systems, smoke control doorsets and their associated seals. Control of high temperature smoke can be achieved with the use of intumescent seals.

Quantitative measurements of smoke leakage through doorsets etc. are achieved by reference to BS 476-31.1:1989.

5.2.2 *Smoke clearance*

This term describes any method of removing relatively cool smoky gases from a space in a building when smoke is no longer entering or being created in that space. This can be achieved by providing natural cross-ventilation, e.g. by the opening of windows, or by activation of powered exhaust systems.

5.2.3 *Smoke dilution*

This term describes any method of mixing the smoky gases with enough clean air to increase visibility and reduce the threat from toxic combustion products. This can require a very large dilution to achieve a safe visibility. With smoky fuels such as those from many plastics materials this dilution may need to be one thousand times the initial volume of combustion gases. This can be difficult to achieve for all except the smallest design fires in a large building volume.

5.2.4 *Smoke exhaust ventilation*

This is a method providing a separation between an upper layer of smoke and a lower layer of relatively clean air. This is achieved by exhausting smoke from the buoyant smoke layer using either natural or powered ventilators, and replacing it with clean air entering the space below the layer.

Hot, buoyant gases from a fire rise to form a stable layer in a reservoir below the ceiling such that a cooler clear layer of sufficient height may be present for long enough to achieve safe evacuation of occupants.

It is rare to find circumstances where a dedicated smoke exhaust ventilation system is required within a small room although the process may play an important part in fire fighting.

Guidance on the design of smoke exhaust ventilation can be found in BS 7346-4 (draft) and BS 7346-5 (draft).

5.2.5 *Pressurization*

Pressurization is a form of smoke control using pressure differentials, in which the air pressure in spaces being protected is raised above that in the fire-affected area. Airflow through the leakage paths prevents infiltration of smoke to the protected high-pressure side.

Guidance on the design of pressurization systems can be found in BS 5588-4:1998.

The pressure difference across any small openings onto an escape route should be large enough to offset the fire-generated pressure as well as any adverse pressures caused by external winds and stack effects. It should also be low enough to allow the escape doors to be opened with relative ease. The requirements can be contradictory and difficult to reconcile.

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Pressurization systems are designed to have adequate air flow rates across any large openings (e.g. doors); excessive pressure difference across a small opening (when the doors are closed) can be prevented by the use of pressure-relief dampers and ducts.

5.2.6 *Depressurization*

Depressurization is smoke control using pressure differentials in which the air pressure in the space containing the fire is reduced below that in the adjacent spaces requiring protection.

Gases are removed from the smoke-affected space in a way that maintains the desired pressure differences across leakage openings between that space and adjacent spaces.

In the special circumstances of an atrium it is sometimes possible to use the buoyancy of the smoky gases themselves to create the desired depressurization effects.

Guidance on the design of depressurization systems can be found in BS 5588-4:1998.

6 Environmental influences on smoke control

The efficiency of any chosen smoke control system can be adversely affected by the wind and outside temperatures. The pressures generated by wind can hamper the extraction of smoke by providing a positive pressure at the extraction point. Internal climatic conditions may also be important.

In rooms of large volume, such as exhibition halls, forced air circulation or solar gain can initially prevent smoke of low buoyancy reaching high level detectors. Stack effects in tall buildings, and temperature inversions between floor and ceiling will also need to be considered.

7 Use of Sub-systems

7.1 General

Each of the Sub-systems 1 to 6 (PD 7974-1 to PD 7974-6) can be used in isolation but for most practical design purposes several Sub-systems will be needed to carry out a full analysis.

During the QDR the main input data for a quantified study will have been established (e.g. building parameters, trial designs, fire scenarios). The basic calculation approach will also have been decided.

7.2 Relationship between Sub-systems

It may be possible to use each Sub-system in isolation given input from the QDR and the source terms from Sub-system 1 (PD 7974-1). It is quite likely though that there will be substantial interdependence between Sub-systems. For instance, the rate of fire growth given by Sub-system 1 (PD 7974-1) can be influenced by the activation of sprinklers (Sub-system 4, PD 7974-4) whose timing is determined by the spread of combustion gases (Sub-system 2). The nature of the links between the various Sub-systems is illustrated by the information bus analogy (see Figure 2).

Evaluating all of the possible interactions is often not practical because of a lack of data or the computational effort required. However, by making appropriate simplifications and utilizing “worst case” assumptions it is generally possible to simplify the calculation process to manageable proportions.

A life safety analysis can involve using five of the six Sub-systems (fire service intervention is normally discounted when designing for the life safety of the initial occupants) whereas when considering structural failure it may only be necessary to consider Sub-systems 1 and 3 (PD 7974-1 and PD 7974-3).

The choice of which Sub-systems are utilized and the manner in which they are linked in the calculation process will therefore depend upon the type of problem being considered and the extent to which it is simplified in the QDR and subsequent quantification process.

7.3 Use of Sub-system 2

Figure 3 outlines the main stages for the analysis of smoke and toxic gases within and beyond the enclosure of origin.

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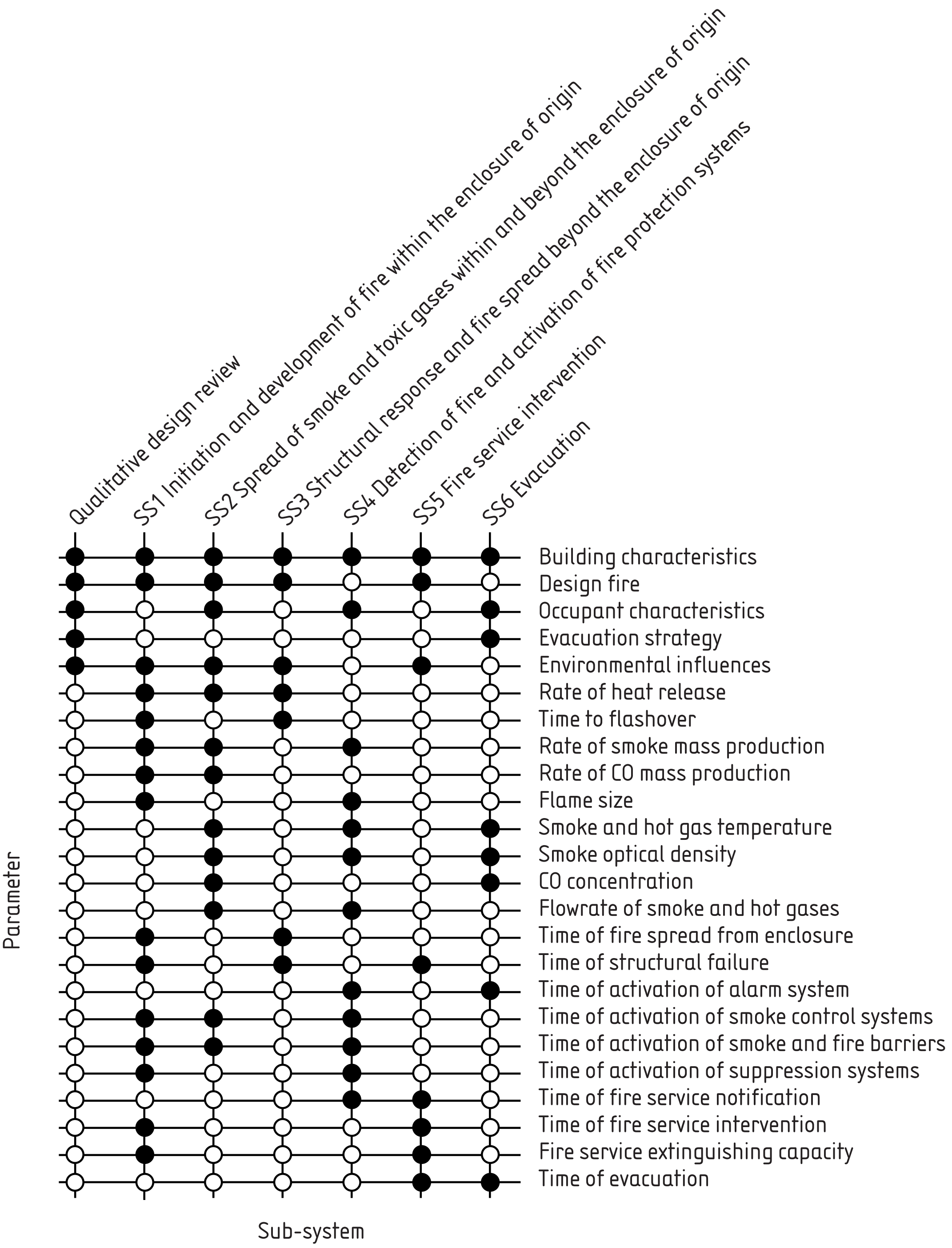

Parameter	Qualitative design review	SS1 Initiation and development of fire within the enclosure of origin	SS2 Spread of smoke and toxic gases within and beyond the enclosure of origin	SS3 Structural response and fire spread beyond the enclosure of origin	SS4 Detection of fire and activation of fire protection systems	SS5 Fire service intervention	SS6 Evacuation
Building characteristics	●	●	●	●	●	●	●
Design fire	●	●	●	●	○	●	○
Occupant characteristics	●	○	●	○	●	○	●
Evacuation strategy	●	○	○	○	○	○	●
Environmental influences	●	●	●	●	○	●	○
Rate of heat release	○	●	●	●	○	○	○
Time to flashover	○	●	○	●	○	○	○
Rate of smoke mass production	○	●	●	○	●	○	○
Rate of CO mass production	○	●	●	○	○	○	○
Flame size	○	●	○	○	●	○	○
Smoke and hot gas temperature	○	○	●	○	●	○	●
Smoke optical density	○	○	●	○	●	○	●
CO concentration	○	○	●	○	○	○	●
Flowrate of smoke and hot gases	○	○	●	○	●	○	○
Time of fire spread from enclosure	○	●	○	●	○	○	○
Time of structural failure	○	●	○	●	○	●	○
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	○	●	○	○	●	○	○
Time of fire service notification	○	○	○	○	●	●	○
Time of fire service intervention	○	●	○	○	○	●	○
Fire service extinguishing capacity	○	●	○	○	○	●	○
Time of evacuation	○	○	○	○	○	●	●

Key
● Likely interactions
○ Potential interactions

Figure 2 — Relationship between Sub-systems

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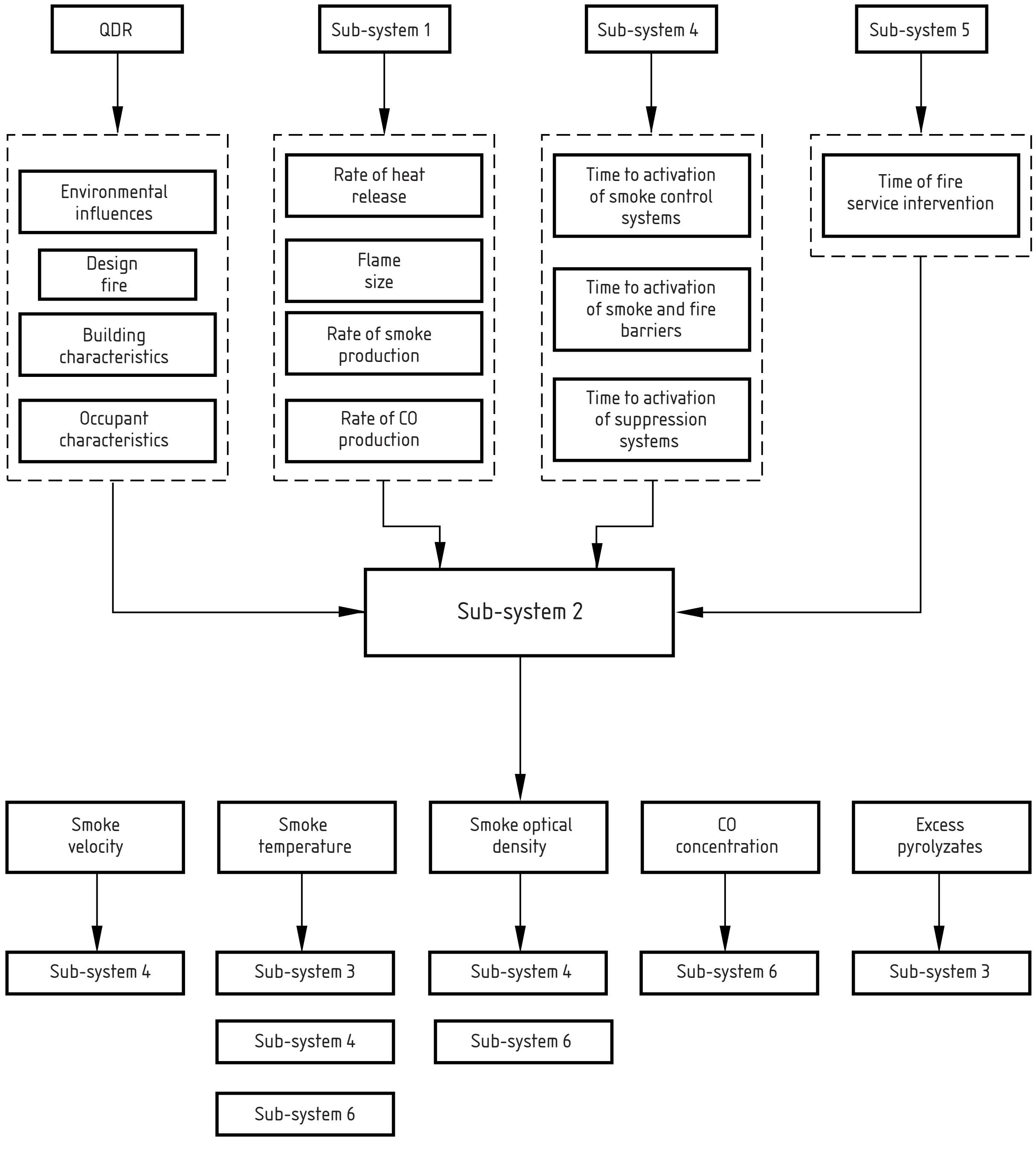

Figure 3 — Stages for the analysis of smoke and toxic gases within and beyond the enclosure of origin

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7.4 Inputs to Sub-system 2

Inputs are summarized in Figure 2 and Figure 3. They are building characteristics, design fire, occupant characteristics and environmental influences available from the QDR and the location and type of detectors, sprinklers and other active measures such as vents, smoke curtains, etc.

The rate of heat, smoke and toxic gas release from the design fires will be available from Sub-system 1 (PD 7974-1). Time of activation of any fire detection and sprinkler system activation will be available from Sub-system 4 (PD 7974-4) possibly following calculated values from this Sub-system of smoke gas velocities and temperatures. The time of activation of smoke and fire barriers will also be provided by Sub-system 4 (PD 7974-4), again possibly following the inputs to it from this Sub-system.

7.5 Locations of interest

During the QDR, the locations of interest in terms of the potential impact of smoke spread should be established. These locations can include:

— the positions where the occupants may be at risk;

— the positions of smoke and heat detectors likely to be first activated;

— the proposed positions of fire detectors linked to active systems, such as self-closing doors, shutters, extinguishing systems, smoke curtains etc.;

— the positions of any contents at risk.

The locations of interest can change over time as the fire develops and spreads. Where several locations of interest are considered, separate sets of calculations may be necessary.

7.6 Outputs from Sub-system 2

Sub-system 2 will provide estimates of smoke property distribution as a function of time throughout the building. The smoke properties will be: gas velocity and temperature; mass flow rates of smoke; unburned fuel and toxic product concentrations. These will be accompanied by estimates of optical density and visibility through the smoke.

The gas velocity and temperature information will be used as input to Sub-system 4 (PD 7974-4) for achievement of detection and suppression activation criteria. The distribution of combustion product concentration and temperature will also be used as input to Sub-systems 3 and 6 (PD 7974-3 and PD 7974-6).

7.7 Smoke characteristics

The characteristics of smoke at any location can be used to establish whether and when local conditions become untenable or whether smoke detectors, heat detectors and suppression systems will be activated.

In most non-industrial cases where typical building contents are burning, loss of visibility, adequate enough for safe escape, occurs before the onset of incapacitating toxic conditions. Visibility through smoke, and the response of smoke detectors, can be determined from the optical density of the smoke. The response of heat detectors can be determined from the smoke temperature. Calculations to establish the concentration of toxic species are generally required only when dealing with unusually toxic combustion products or when visibility is not a critical life safety criterion.

7.8 Calculation procedures and the role of computer modelling

A large variety of engineering methods of differing levels of complexity are available to evaluate the spread of smoke and toxic gases. They include estimation formulae, computer simulation models and experimental methods.

Most of the detail presented here involves the use of individual estimation formulae to describe the component parts of the problem, e.g. the smoke flow from the fire source, the flow out of the enclosure of origin, the flow rising above a balcony, the optical density of the smoke at any point etc, etc.

However, many of these individual treatments, and more, are included within a wide range of computer simulation models currently available. These can provide full simulations of the whole process including the analyses provided in the other Sub-systems and these are discussed in Annex A.

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Use of these simulation models can blur the sharp boundaries between Sub-systems. For example a single computer simulation model may be able to provide a fully coupled link between the variables discussed in Sub-systems 1, 2, 3, 4 and possibly 5. Given a chosen growing design fire, the model will not only be able to provide details of the smoke filling of a building space but will also calculate when the conditions for fire detection or sprinkler activation are achieved. At detection the model can now simulate the consequences of various smoke ventilation strategies and their impact on the occupants. At calculated activation of the first sprinkler, the design fire growth can be modified according to the guidance provided in Sub-system 1 (PD 7974-1) to allow for the effects of sprinkler operation on the heat release rate from the design fire.

Two distinctly different types of computer fire model are available to assess proposed designs. Known as zone and field (or Computational Fluid Dynamics) models, they differ primarily in their treatments of the gas phase. The theoretical basis of the two approaches to modelling has been discussed in some detail elsewhere, e.g. references [7],[8]. More information is provided on these approaches in Annex A.

The zonal method is very similar in approach to that adopted in Clause **9** and relies on assembling a relatively small number of equations similar or identical to those described here, each of which describe, to the desired level of accuracy, a recognized "component" of the overall system. Typical components will be the thermal plume rising above the fire source, a ceiling layer of hot combustion products spilling over an "inverted" weir above an open window or over a balcony.

No one zone model can be expected to cover all classes of problem since they are based largely on *a priori* assumptions, guided by experience and observation, on how fires develop in particular environments.

The influences on smoke movement within a small office or hotel bedroom might be very different from those, say, within a very large atrium which require different zonal components.

More sophisticated CFD models instead exploit the latest techniques used for the simulation of fluid flow throughout the full breadth of engineering application. These solve directly, throughout the domain of interest (using numerical methods) the three dimensional, time-dependent equations describing the laws of conservation subject to the particular boundary conditions of the problem. These equations are not those presented in Clause **9** but are instead universal equations governing fluid flow and heat transfer.

The viability of these more sophisticated models is critically dependent on the speed and memory of modern computer "hardware". Though these models are more complex and expensive to run than the zonal models they are more universally applicable, not being dependent on the a priori assumptions on smoke movement of the zonal treatment.

The flow chart provided in Annex B (Figure B.1) is indicative of the calculation procedures required.

Experimental methods can also be used to evaluate the effectiveness of a particular design itself based on one or more of the theoretical approaches. These range from small scale modelling using heated gas or helium to represent the buoyancy of the fire through salt water analogues [9] to full scale "hot smoke" tests [5], [10].

8 Design procedure

8.1 General

To ensure that the smoke control system is adequate for its purpose, calculations are necessary to estimate the properties of the smoke likely to be encountered at various locations and at various times within the design. Given particular design options and design fires from the QDR and Sub-system 1 (PD 7974-1), the primary concern is to evaluate the degree of air entrainment into the buoyant combustion products that emerge from the fire. This is because it is these large volumes of air that dominate the mass, volume and temperature of the smoke and its toxic gas concentrations.

Consideration needs to be given to where air entrainment will occur and to calculate the consequences of this entrainment on the key properties. This can be achieved by exploiting the individual equations provided in a design sequence or alternatively by exploitation of computer simulation tools. The different classes of model are described briefly in **7.8** and in more detail in the Annex A.

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8.2 Inputs to Sub-system 2

8.2.1 *Building characteristics*

The dimensions and geometry of the enclosures and buildings, including proposed location of detectors, suppression systems and other active protection systems should be obtained from the QDR together with details of escape routes and places of refuge. The thermal properties and the surface roughness of bounding surfaces can have a substantial influence on heat and momentum losses from ceiling jets and hot gas layers.

Trial fire safety designs including choice of smoke management system proposed and location and type of any vents will be available from the QDR.

8.2.2 *Occupant characteristics*

The numbers and locations of occupants likely to be at risk needs to be supplied by the QDR. These should include any factors that may have particular impact on occupant escape e.g. their mobility, alertness, familiarity with the building etc. Guidance on these matters is provided in Sub-system 5 (PD 7974-5).

8.2.3 *Design fire*

The starting point will be the design fire. The type of fire will be supplied by the QDR with its characteristics (heat, smoke and species release rates) provided by Sub-system 1 (PD 7974-1). The decision will be made in the QDR as to whether, for design purposes, the fire will be considered to be steady or time-dependent.

The time-dependent design fire should provide the physical size and heat output of the fire changing with time in a realistic manner, allowing the growing threat to occupants, property and fire-fighters to be calculated as time progresses. Such time-based calculations of the evolving hazard usually have to be compared with separate assessments of the time available for safe escape of the occupants and for initiation of successful fire-fighting. These calculations are discussed in Sub-systems 5 and 6 (PD 7974-5 and PD 7974-6).

The alternative assumption of a steady fire allows the smoke control system to cater indefinitely for all fires up to design fire size effectively allowing the occupants an indefinite time for escape. This has the merit of not requiring occupant evacuation times to be calculated.

It should be noted that what may be a “worst case” choice for one design objective may be a “best case” for another. For example, a large or fast growing design fire may ensure a conservative estimate of smoke exhaust capacity required but can also produce a far too optimistic estimate of detection time.

8.2.4 *Environmental influences*

The QDR will need to provide data on:

a) the likely influences of wind on the building, since wind-induced pressures can have an impact on any smoke control measures;

b) internal air movements due to the normal heating and ventilating systems; these can have a particularly significant impact on early fire detection;

c) stack effects in tall buildings. The possibility of temperature inversions between floor and ceiling will also need to be considered.

8.2.5 *Active system activation times*

These will be provided by Sub-system 4 (PD 7974-4) but computer modelling of smoke movement in this Sub-system may allow these times to be determined here based on the criteria for active system operation from Sub-system 4.

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9 Analysis

9.1 Heat content of plume

Not all the heat released by the fire source is convected away by the plume. A substantial fraction, typically 20 to 40 %, is lost to the surroundings by radiative heat transfer from the flames. For engineering purposes this is often written:

$$Q_p = \chi Q \tag{1}$$

where

χ	is the fraction of the total heat release convected by the plume; This can range typically from 0.4 to 0.9 depending on the fuel (data for particular fuels are provided in Clause **11**, Table 1).
Q_p	is the rate of heat release convected by the plume;
Q	is the total rate of heat release of the fire source.

9.2 Smoke plumes above fire source

9.2.1 *General*

Relationships are presented for the mass flow rates of smoke generated by fires. These are based upon the air entrained into the fire plumes. They are based on both theory and experimental data. Except where stated the mass flow rate of fuel is negligible when compared with that of the entrained air and is not taken into account.

At a given height, entrainment depends on the heat release rate of the fire and at small plume heights on the geometry of the source.

9.2.2 *The axi-symmetric plume*

The products of combustion from a fire are hot and therefore buoyant. The products rise away from the fire source entraining air from the surroundings. This air mixes with the products of combustion to dilute, cool and to slow the resulting plume but increasing the total volume of smoke threatening the occupants of a building. In the early stages details of the enclosure will have little influence although ambient air-flows will. See **9.2.6**.

As the fire grows then details such as the location of openings such as doorways or windows and the proximity of walls will influence not only the rate of heat release of the fire but also the entrainment of air and consequently the volumes of smoke produced.

For most fires away from walls, the plume can be considered to be undisturbed and axi-symmetric. The mean height of luminous flames for fires of $Q^* \geq 1$ is given by [11], [12]:

$$z_{fl} = 3.3Q^{*2/5}D_s \tag{2}$$

or more simply

$$z_{fl} = 0.2Q^{2/5} \tag{3}$$

where

$$Q^* = \frac{Q}{\rho_0 T_0 C_p g^{1/2} D_s^{5/2}} = \frac{Q}{1110 D_s^{5/2}} \text{ for “normal” ambient conditions} \tag{4}$$

NOTE 1 Q^* describes the relative contributions of buoyancy and momentum at the source. Q^* for buoyant fires ranges from close to zero to around 2.0. Fires with Q^* above this are closer to jet fires and more characteristic of gaseous leakages from pipes etc.

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When $Q^* << 1$, then different expressions apply, [12], but equation (3) represents an upper limit for the flame height.

NOTE 2 For $Q^* << 1$, Heskestad's expression [13] can be used which can be written:

$$z_{\text{fl}} = 3.7Q^{*2/5}D_s - 1.02D_s \tag{5}$$

NOTE 3 Since equations (3) and (5) do not agree perfectly at $Q^* = 1$, the more conservative choice should be taken where there is doubt.

In the "far field" of such fires (when $z > 5D_s$) then the mass flow rate of smoke, a distance z above the fuel surface, is [14]:

$$m_{\text{smoke}} = 0.071Q_p^{1/3}(z - z_0)^{5/3} \tag{6}$$

where

D_s is the linear dimension of the source;

z is the height of the plume above fuel surface;

z_0 is the height of the virtual source above the fuel surface;

Q_p is the convective heat output of the fire.

NOTE 4 Here: $z_0 = -1.02D_s + 1.38Q^{*2/5}D_s$ [13] (7)

NOTE 5 z_0 is usually negative meaning that the virtual source is located below the fuel surface (see Figure B.2).

In the near field, below the visible flame height z_{fl}, the mass flow rate of air entrained into the fire is [15]:

$$m_{\text{air}} = 0.19pz^{3/2} \tag{8}$$

where

p is the perimeter of the source; and

m_{smoke} = m_{air} above the flame height).

NOTE 6 This expression is strictly only valid below the flame tip but can be used above it for $z < 10D_s$.

Although equation (8) does give reasonable estimates for smoke mass flow rate above the visible flame height, its lack of explicit dependence on Q, requires special care to be exercised when undertaking sensitivity studies in conjunction with other equations that are Q dependent. In exploring sensitivity to design fires it can often be assumed that the heat release rate per unit area is constant for a particular fire type. There is then a simple relationship between p and Q, e.g. for a square fire:

$$Q = \frac{Q''p^2}{16} \tag{9}$$

Where Q'' is the heat release rate per unit area of fire. This implies that $m_{\text{smoke}} \infty Q^{1/2}$ in equation (8) rather than $Q^{1/3}$ in equation (6).

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9.2.3 *The line plume*

Rectangular fire sources with the longer side greater than five times the shorter side can be treated as line fires. Here the flame length is [16], [17].

$$z_{\mathrm{fl}} = 0.035\left(\frac{Q}{d_{\mathrm{s}}}\right)^{2/3} \tag{10}$$

where

d_{s} is the longer linear dimension of the source;

and the mass flow rate of smoke, a distance z above the fire, up to $z < 5d_{\mathrm{s}}$ will be [18]:

$$m_{\mathrm{smoke}} = 0.21Q_{\mathrm{p}}^{1/3}\, d_{\mathrm{s}}^{2/3} z \tag{11}$$

In the far field when $z < 5d_{\mathrm{s}}$, the plume will be close to axisymmetric and equation (6) may be used.

9.2.4 *Effect of adjacent walls*

When a fire occurs close to a wall or in a corner then air can only be entrained over a part of the fire perimeter. This causes flames to lengthen and reduces the resulting mass flow rates of smoke.

Mass flow rates are not simply halved or quartered but can be estimated as follows. Equations (12) to (15) presented here exploit a “mirror” image assumption to establish the appropriate relationships from the axisymmetric equations (3) and (6) whilst equations (16) and (17) are modifications to equation (8).

For fires of $Q^* \geq 1$ flame length against a wall becomes [20]:

$$z_{\mathrm{fl}} = 0.26Q^{2/5} \tag{12}$$

and in a corner

$$z_{\mathrm{fl}} = 0.35Q^{2/5} \tag{13}$$

The mass flow rate of smoke in the far field of a fire against a wall and in a corner when $z > 5D_{\mathrm{s}}$ become respectively:

$$m_{\mathrm{smoke}} = 0.044Q_{\mathrm{p}}^{1/3}\,(z - z_0)^{5/3} \tag{14}$$

and

$$m_{\mathrm{smoke}} = 0.028Q_{\mathrm{p}}^{1/3}\,(z - z_0)^{5/3} \tag{15}$$

In the near field, below z_{fl}, equation (8) may be modified to allow entrainment from either three quarters or half of the overall perimeter of the fire i.e. the mass flow rates of smoke from wall and corner fires become respectively [21].

$$m_{\mathrm{smoke}} = 0.14pz^{3/2} \tag{16}$$

and

$$m_{\mathrm{smoke}} = 0.09pz^{3/2} \tag{17}$$

NOTE There has been insufficient testing of these models against experimental data see [19] for a discussion of this issue. Results are only indicative and it is likely that equations (12) and (13) provide an over-prediction of flame height whilst equations (14) to (17) provide an underprediction of smoke mass flow rate. Depending upon the whether the critical condition is smoke mass flow rate or smoke concentration then the most conservative choice between wall-affected and free plumes should be chosen.

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9.2.5 *Effect of fire-induced winds*

A fire plume in a small compartment or close to an enclosure opening can be deflected away from it as a result of the fire-induced jet of entrained air through the opening. The consequence is that flame heights and lengths near such openings can be disturbed as will mass flow rates of smoke. This can cause additional air entrainment into the plume and therefore smoke mass flow rates in such circumstances can increase substantially. One way to calculate for this in the near field, i.e. when $z > 5D_s$, is to increase the constant of proportionality in equation (8) [21]:

$$m_{\text{smoke}} = 0.34pz^{3/2} \tag{18}$$

NOTE The comments following equation (8) apply equally here. Alternative, more flexible, treatments based on the influence of a cross-wind on equation (6) will be found in [22].

9.2.6 *Stratification of smoke*

When the ambient air temperature above the fire source is significantly higher than that being entrained into it at lower level, due for example to solar or space heating of the volume concerned, then the plume will stop rising before it reaches the ceiling (Figure B.3). This is because it has now lost its buoyancy relative to its warmer surroundings. Although this situation will eventually be overcome in time as the fire continues to grow, it can have significant consequences for the early detection of fire.

The maximum heights of rise of axi-symmetric and line plumes against an ambient temperature gradient of $\dfrac{\Delta T}{\Delta z}$ are respectively [23,24]:

$$z_{\max} = 5.54 Q_p{}^{1/4}\left(\frac{\Delta T}{\Delta z}\right)^{-3/8} \tag{19}$$

$$z_{\max} = 4.81\left(\frac{Q_p}{d_s}\right)^{1/3}\left(\frac{\Delta T}{\Delta z}\right)^{-1/2} \tag{20}$$

NOTE Equation (19) has been reasonably well validated against data but equation (20) has yet to be tested.

9.3 Ceiling jets

9.3.1 *General*

When a fire plume impinges on a ceiling, the flow of smoky 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 needs to be known to enable detector and sprinkler activation times to be assessed since this is where such devices are usually installed. The gases initially move away from the impingement point in an axi-symmetric ceiling jet until it impinges bounding walls, beams etc. Ceiling jets are typically 5 % to 12 % of the fire source-to-ceiling height in depth. 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 [25] calculate the maximum temperature and velocity in the ceiling jet. If detectors or sprinkler heads are situated substantially lower than this distance then lower values than those quoted should be expected leading to longer activation times.

For time-dependent design fires, the following equations can be assumed to be quasi-steady and the time-varying Q, obtained from Sub-system 1 (PD 7974-1), inserted into the appropriate equation. This is reasonable in relatively small enclosures where the transit time of the smoke from fire to detector is low but where this is likely to exceed around 10 seconds special consideration needs to be given. CFD fire models can be of particular assistance with these problems.

Treatments for the effects of surface roughness and of heat loss can be found in [25], [26] or can be incorporated by use of computer models.

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9.3.2 *Axi-symmetric ceiling jet*

The maximum temperatures and velocities in an unconfined axi-symmetric ceiling jet under a smooth ceiling produced by a steady fire are [26]:

$$\theta_{\max} = \frac{16.9}{H^{5/3}} Q^{2/3} \qquad \text{for } \frac{r}{H} < 0.18 \tag{21}$$

$$\theta_{\max} = \frac{5.4}{H}\left(\frac{Q}{r}\right)^{2/3} \qquad \text{for } \frac{r}{H} > 0.18 \tag{22}$$

$$u_{\max} = 0.96\left(\frac{Q}{H}\right)^{1/3} \qquad \text{for } \frac{r}{H} < 0.15 \tag{23}$$

$$u_{\max} = 0.2Q^{1/3}\,\frac{H^{1/2}}{r^{5/6}} \qquad \text{for } \frac{r}{H} > 0.15 \tag{24}$$

where

$\theta_{\max}$ is the maximum temperature rise in the ceiling jet;
$u_{\max}$ is the maximum gas velocity in the ceiling jet;
r is the radial distance from the ceiling impingement point;
H is the height of the ceiling above the fire source.

NOTE These equations assume that the jet is moving through ambient air and is not submerged within a ceiling smoke layer.

9.3.3 *Two-dimensional ceiling jet*

The two-dimensional ceiling jet that develops downstream of an axi-symmetric ceiling jet impinging bounding vertical surfaces such as beams or corridor walls can be described by its slow decrease in temperature and velocity [27]:

$$\theta_{\max} = 0.29\theta_{\text{imp}}\left(\frac{H}{l}\right)^{1/3} \exp\left\{-0.2\left(\frac{y}{H}\right)\left(\frac{l}{H}\right)^{1/3}\right\} \qquad y > l \tag{25}$$

and

$$u = 0.39\left(\frac{H}{l}\right)^{1/6}\left(\frac{gH\theta_{\max}}{T}\right)^{1/2} \qquad y > l \tag{26}$$

where

θ_{imp} is the maximum temperature rise in the vertical plume at the impingement point;
l is the corridor half width;
y is the distance along the corridor from the impingement point.

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9.4 Flow from enclosure openings

9.4.1 *General*

The mass flow rate of smoke from a vertical opening of width, w, greater than its height, h, before the onset of flashover is [28]:

$$m_{\mathrm{smoke}} = 0.09h(Q_{\mathrm{p}}w^2)^{1/3} \tag{27}$$

An alternative presented in terms of the gas temperature is [5]:

$$m_{\mathrm{smoke}} = \frac{2}{3}C_d^n(2g\theta T_0)^{1/2}\left(\frac{w\rho_0}{T}\right)d^{3/2}\kappa_{\mathrm{m}} \tag{28}$$

where

C_{d}	is a discharge coefficient for the opening-0.6 for an opening with a deep downstand or 1.0 for no downstand [5];
d	is the depth of smoke layer in the opening;
κ_{m}	is a “profile correction factor” to allow for departure from a step function for the vertical temperature gradient (κ_{m} is 1.0 for a step function but can be taken as 1.3 for most hot gas layers where θ is less than 300 C);
θ	is the maximum temperature rise in the hot gas layer at the opening;
T	is the maximum temperature in the hot gas layer at the opening ($T = T_0 + \theta$);
T_0	is the ambient air temperature;
ρ_0	is the ambient air density;
and $n = 1.5$	for an opening much wider than the hot gas layer depth ($w >> d$);
$n = 1$	for openings much narrower that the hot gas layer depth ($w << d$).

The smoke layer depth can be obtained by equating the mass outflow, equation (28) with the mass entrainment rate of air into the plume from equation (6), (8) or (18). For equations (8) or (18) this becomes:

$$d = \frac{(C_{\mathrm{e}}p)^{2/3}h}{\left[(C_{\mathrm{e}}p)^{2/3} + w^{2/3}\left\{\frac{2}{3}\frac{C_d^n\rho_0\kappa_{\mathrm{m}}}{T}(2g\theta T_0)^{1/2}\right\}^{2/3}\right]} \tag{29}$$

Here C_{e} is the constant of proportionality in equation (8) or (18); 0.19 or 0.34 respectively.

The smoke outflow resulting from equating the plume entrainment and outflow is then:

$$m_{\mathrm{smoke}} = \frac{C_{\mathrm{e}}ph^{3/2}w}{\left[w^{2/3} + \frac{1}{C_{\mathrm{d}}}\left(\frac{C_{\mathrm{e}}p}{\kappa}\right)^{2/3}\right]^{3/2}} \tag{30}$$

where

$$\kappa = \left(\frac{2}{3}\frac{\rho_0}{T}\sqrt{2g\theta T_0 \cdot \kappa_{\mathrm{m}}}\right) \tag{31}$$

NOTE κ takes a value of 2.35 ± 0.07 kg·s^{-1}·m$^{-5/2}$ for θ between 200 °C and 1 000 °C, below 200 °C it decreases to for example 1.54 at 50 °C.

Similar calculations can be conducted by coupling of equations (6) and (28) but iterative methods are needed for solution of the resulting equation.

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9.4.2 *Spill plumes*

The equations (2) to (31) presented above permit the mass flow rates of smoke and combustion products emanating from the fire enclosure to be assessed. Where these cannot be confined to the enclosure of origin or its immediate vicinity it is likely that additional air entrainment will occur en route to remote smoke vents.

This entrainment will be dependent on details of the design. A particularly common problem is that associated with spilling of smoke over a balcony edge into a large void. The larger the height of rise of the plume and indeed the larger its surface area the greater the mass of air entrained into the flow and therefore the greater the mass flow rate of smoke that needs to be dealt with. This additional mass flow rate can often be much greater than that emanating from the fire enclosure itself.

There is still considerable uncertainty associated with the assessment of this additional air entrainment. A large variety of approaches are available. Only the simpler are presented here. Alternatives to the use of these are the BRE method [5] or CFD models (see reference [30], for example).

The additional mass flow rate of air entrained into a free plume rising above a balcony edge with no entrainment into the ends of the plume but where its lateral extent, L, and smoke depth in the layer approaching the spill edge, d, are known (Figure B.4 and Figure B.5) is [31]:

$$m_{\mathrm{air}} = 0.16 Q_{\mathrm{p}}^{1/3} L^{2/3} (z + d) \tag{32}$$

where

L is the lateral extent of the spill plume, e.g. the distance between channelling screens;

d is the smoke layer depth at the balcony edge.

NOTE 1 This expression results from analysis of experimental data suggesting that in the far field the spill plume behaves as though it has emerged from a virtual line source a distance, d, below the balcony edge.

Alternatively [32] this may be written:

$$m_{\mathrm{air}} = 0.16 Q_{\mathrm{p}}^{1/3} L^{2/3} z + 0.0014 Q_{\mathrm{p}} + 0.4 m_{\mathrm{b}} \tag{33}$$

where

m_{b} is the mass flow rate of smoke approaching the balcony.

The total mass flow rate of smoke above the spill edge is:

$$m_{\mathrm{smoke}} = m_{\mathrm{b}} + m_{\mathrm{air}}$$

NOTE 2 This expression results from dimensional analysis of the same data as were used for equation (32) but without the assumption of a virtual source. The two expressions agree with each other but equation (32) requires knowledge of d.

They both agree reasonably well with the "BRE method" [5] when it uses a lower assumed air entrainment constant ($\alpha = 0.11$) instead of the original ($\alpha = 0.16$) taken from the Lee and Emmons [17] line plume treatment. There is a growing body of evidence to support a reduction of entrainment coefficient (see [17] for a summary).

Although it is possible to adjust equations (32) and (33) to allow for entrainment into the ends of the spill plume, experimental evidence to support them is inadequate. An alternative approach [33] for flow that is channelled by vertical screens before spilling over the balcony edge suggests that the total mass entrained, including the end effects is:

$$m_{\mathrm{smoke}} = m_{\mathrm{b}} + m_{\mathrm{air}} = 0.36 Q_{\mathrm{p}}^{1/3} L^{2/3} (z + 0.25H) \tag{34}$$

This expression, which does not require a knowledge of smoke layer depth includes entrainment into the spill plume ends as well as the approach flow.

NOTE 3 Equation (34) uses an assumption, based on evidence from small scale experiments that the smoke above the balcony behaves as though it were emerging from a "virtual origin" a distance 0.25 H below the balcony edge. Equation (32) instead assumes that this "virtual origin" is not fixed but at a distance, d, below the balcony edge. Equation (33) makes no assumptions about a virtual origin. Although convenient to use these equations are based on relatively few data.

The different constants of proportionality in equations (32) and (34) are caused by the inclusion of end effects and reflect a different degree of entrainment observed in smoke reservoirs of different aspect ratio.

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Where the smoke flow is not channelled between the enclosure opening and the spill edge, Figure B.6, reference [33] recommends that equation (26) be modified to:

$$m_{\text{smoke}} = m_{\text{b}} + m_{\text{air}} = 0.36 Q_{\text{p}}^{1/3} (w + b)^{2/3} (z + 0.25H) \tag{35}$$

where

w	is the width of the opening on to the balcony;
b	is the horizontal distance from the opening to balcony edge.

NOTE 4 At very large heights, i.e. $z > 5L$ or $z > 5(w + b)$, the plume can be considered axi-symmetric and entrainment calculated from equation (2) with $z_0 = 0$ if this gives a more conservative solution.

Equations (34) and (35) are based on relatively few data and are intended for the assessment of smoke mass flow rates only. Equation (35) is unlikely to be general in application but can be used for b less than or equal to w. It should not be used to indicate the width of flow under the balcony. Where there is uncertainty as to the degree of smoke spreading underneath a balcony the use of CFD modelling should be considered.

For practical application it is recommended that evaluation of each approach is necessary and the more conservative chosen depending on whether the critical condition is for smoke mass flow rate or smoke temperature or gas concentration.

Where it is clear that the spill plume will attach to a wall above the balcony edge the air entrained and therefore the mass flow rate of smoke will be reduced. This is because air can now be entrained from only one side and furthermore turbulent mixing is reduced by the stabilizing effect of the wall. Simple estimates based on the measurements of Grella and Faeth [34] suggest that the mass flow rate of smoke can be as low as between 30 % and 50 % of the free plume condition.

9.4.3 *Flow of hot gases through natural horizontal vents*

The mass flow rate of smoke from horizontal natural vents is [15]:

$$m_{\text{smoke}} = A_{\text{v}} C_{\text{v}} \rho_0 \left(\frac{2gd\theta T_0}{T^2 + \left(\dfrac{A_{\text{v}} C_{\text{v}}}{A_{\text{i}} C_{\text{i}}}\right)^2 T_0 T} \right)^{1/2} \tag{36}$$

where

A_{v}	is the throat area of the ventilator;
C_{v}	is the coefficient of discharge;
A_{i}	is the total area of all inlets;
C_{i}	is the entry coefficient for inlets.

When recast in terms in terms of vent area, equation (36) becomes:

$$A_{\text{v}} = \frac{m_{\text{smoke}} T}{C_{\text{v}} \left(2gd\rho_0^2 \theta T_0 - \left[\dfrac{T T_0 m_{\text{smoke}}^2}{A_{\text{i}}^2 C_{\text{i}}^2} \right] \right)^{1/2}} \tag{37}$$

This can be rearranged to allow vent area to be determined in terms of Q, using equation (36). For very large inlet areas:

$$A_{\text{v}} = \frac{m_{\text{smoke}}^{3/2} T_0^{1/2} C_{\text{p}}^{1/2}}{\rho_0 C_{\text{v}} (2gd)^{1/2}} \cdot \frac{1}{Q_{\text{p}}^{1/2}} \left[1 + \frac{Q_{\text{p}}}{m_{\text{smoke}} C_{\text{p}} T_0} \right] \tag{38}$$

NOTE In using equation (8) for an estimate of m_{smoke}, its lack of explicit dependence on Q, requires special care to be exercised when undertaking sensitivity studies in conjunction with equations (36) and (38). It is advisable in determining sensitivity of A_{v} to fire size to ensure that Q'' remains constant.

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9.5 Replacement air

It is essential to ensure that provision is made to allow for make-up or replacement air to replace the smoke mass being vented by either natural or mechanical means.

The incoming airflow through escape doors should not exceed 5 ms^{-1} to permit unimpeded escape. See Sub-system 6 (PD 7974-6).

9.6 Properties of the smoke

9.6.1 *Temperature of the hot gases*

A spatially averaged temperature of hot gases above the flaming region of a fire can be obtained from the local mass flow rate assuming a well-mixed layer and conservation of heat:

$$\theta = \frac{Q_\mathrm{p}}{m_\mathrm{smoke} C_\mathrm{p}} \tag{39}$$

where

C_p is the specific heat of air at constant pressure.

Where the gas layer is particularly large or where heat losses are likely to be significant a numerical modelling treatment is likely to be necessary.

9.6.2 *Smoke volume flow rate*

The volume flow rate of a well-mixed layer of smoke at a particular location will be:

$$V = m_\mathrm{smoke} \frac{T}{\rho_0 T_0} \tag{40}$$

where

T is the local smoke temperature;

T_0 is the ambient air temperature;

ρ_0 is the ambient air density.

NOTE As with equations (36), (37) and (38) it is advisable in determining sensitivity of V to fire size when using equation (8) for m_smoke to ensure that Q'' remains constant.

9.6.3 *Optical density of smoke*

Poor visibility through smoke is often the first effect of fire to hamper occupants making their escape. Light is attenuated by smoke according to the expression:

$$I = I_0 e^{-\mathrm{Ks}} \tag{41}$$

where

I is the light intensity a distance, s, from an observed object of intensity I_0;

K is the extinction coefficient.

This is often given in terms of a base of 10 rather than the exponential function:

$$I = I_0 \cdot 10^{-\mathrm{Ds}} \tag{42}$$

where

D is the optical density of the smoke per unit path length (and $D = 2.3K$).

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From a specified mass of material in a given volume, D is given is given by:

$$D = \frac{D_m f_b}{V_t} \tag{43}$$

where

D_m is the mass optical density for the fuel concerned;
V_t is the total volume of smoke;
f_b is the total mass of fuel burnt.

This assumes a homogeneous distribution of smoke throughout the volume of interest. As with the temperature distribution in **9.6.1**, a numerical modelling treatment will be necessary if this assumption is not valid or where more detailed local information is required.

For the flowing case:

$$D = \frac{D_m m_{fuel}}{V} \tag{44}$$

where

V is the volume flow rate of smoke.

Some typical values for D_m are provided in Table 2 and Table 3 of Clause **11**.

9.6.4 *Visibility through smoke*

Visibility through smoke can be related to its optical density. It has been found experimentally that for practical purposes these can be related very approximately by [36]:

$$S = \frac{1}{D} \tag{45}$$

where

S is the visibility distance through smoke;
D is the optical density per unit length from equation (43) or (44).

This relationship is dependent on the available illumination and where a sign is "back illuminated" its visibility distance is increased by a factor of approximately 2.5.

NOTE D the optical density per unit length is sometimes quoted in decibels per unit length. The right hand sides of equations (43) and (45) are then increased by a factor 10.

9.6.5 *Gas species mass concentrations*

The mass concentration, c_α, of a particular chemical species is given by:

$$c_\alpha = \frac{Y_\alpha f_b}{V_t} \tag{46}$$

where

Y_α is the mass yield of the species α.

Values of Y_α for carbon monoxide are listed in Table 2 and Table 3 of Clause **11**. More fuel data are presented in [34]. As for the temperature distribution above, a numerical modelling treatment will be necessary if this assumption is not valid or where more detailed local information is required.

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9.6.6 *Gas species volume concentrations*

The volume concentration, C_α, is given by:

$$C_\alpha = \frac{c_\alpha}{\rho_\alpha} \tag{47}$$

where

ρ_α is the density of the species α. For CO, ρ_α is 1.25 kg/m^3.

These concentrations may be compared with the tenability criteria provided in Sub-system 5 (PD 7974-5).

9.7 Smoke reservoir size

Smoke collecting in a reservoir will lose heat and therefore buoyancy to its bounding surfaces. This heat loss will depend upon the thermal properties of the surfaces and will increase with surface area. There will therefore be an upper limit to reservoir area beyond which the gases will not remain buoyant undermining the principle of exhaust ventilation.

In the absence of computer modelling it became common practice to specify the maximum area for a naturally ventilated smoke reservoir at 2 000 m^2 for the protection of escape routes, rising to 2 600 m^2 for powered ventilators to prevent this situation occurring. This limit rose to 3 000 m^2 for the protection only of property. Somewhat different criteria have been adopted for shopping malls based on the same principles.

These limitations can be overcome by the use of computer modelling techniques that permit such losses to be incorporated.

9.8 Minimum number of exhaust points

The number of exhaust points within the reservoir is important since, for any specified layer depth, there is a maximum rate at which smoky gases can enter any individual exhaust point. Any further attempt to increase the rate of exhaust through that exhaust point merely serves to draw fresh air into the orifice from below the smoke layer.

This phenomenon is sometimes known as “plug-holing”. Where plug-holing is present, part of the installed exhaust capacity is being “wasted” by drawing clean air into the orifices of the ventilators instead of smoky gases.

It follows that, for efficient exhaust, the number of exhaust points should be chosen to ensure that no air is drawn up in this way.

The critical exhaust rate, m_{crit}, for a ventilator away from a wall is given by [5]:

$$m_{\text{crit}} = \frac{2.05\rho_0(gT_0\theta)^{0.5}d^2w_{\text{v}}^{0.5}}{T} \tag{48}$$

where

m_{crit}	critical exhaust rate at an exhaust point prior to the onset of plug-holing (kgs^{-1});
ρ_0	density of air at ambient temperature (kgm^{-3});
g	acceleration due to gravity (ms^{-2});
d	depth of smoke layer below the exhaust point (m);
T_0	absolute ambient temperature (K);
θ_1	excess temperature of smoke layer (°C);
w_{v}	characteristic width of the ventilator (m) (e.g. the diameter, or the diameter of the circle of the same area).

The equation shows that the critical exhaust rate increases rapidly with increasing layer depth and suggests that a number of small ventilators are preferable to a single large ventilator to optimize the exhaust efficiency.

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Proximity to a wall will reduce the available smoke discharge capacity. The critical exhaust flow will reduce by about 30 % [35].

The required number of extract vents (N) is then given by:

$$N \geq \frac{m}{m_{\text{crit}}} \tag{49}$$

where

m the mass flow rate entering the layer.

Where sprinklers are installed and additional cooling of the smoke layer needs to be accounted for, the number of exhaust points required can be determined by calculating the critical exhaust rate for an opening using equation (48).

9.9 Interactions between sprinklers and smoke ventilation

Sprinkler systems and smoke ventilators are both important for life safety and for property protection objectives. Frequently therefore both sprinklers and smoke ventilators will be used together. The contribution that smoke ventilation will make to life safety is to remove hot and noxious gases and to maintain sufficient visibility to enable occupants to make their escape. The main contribution that it will make to property protection is to make fire-fighting easier and faster.

Automatic sprinkler systems have a major impact on the protection of property against fire and if they operate early enough during the fire growth can also have a life safety role. Their effect is to reduce the frequency of large fires.

In the preceding text, methods have been presented to allow smoke properties to be calculated as a consequence of fire within a building. The impact of sprinkler sprays on controlling the rate of fire growth has only been considered. However, the downward momentum of sprinkler sprays activated at some distance from the fire source can have a deleterious effect on the efficiency of smoke ventilation systems. The presence of smoke ventilation can also delay the activation of the suppression system. The combined effects of entrainment of smoky gases into downward directed sprays as well as buoyancy reduction due to the cooling effects of the sprays needs to be considered. Guidance on these issues is provided in, for example, reference [5].

9.10 Free hanging smoke curtains

9.10.1 *General*

Smoke curtains can either be fixed or movable. The latter are usually designed to drop vertically in response to an appropriate signal. Where these are not guided by vertical channels but are free hanging their length should be adequate to contain the smoky gases without spillage due to horizontal deflection by buoyancy and fan induced pressure differentials. This is only likely to be problematic when curtains are deep or the bottom bars light.

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9.10.2 *Curtains containing a smoke layer*

The deflection of a curtain used to create a smoke reservoir and not reaching down to floor level thus admitting air beneath it, is [5]:

$$D_c = 1.2\frac{\rho_0 \theta d^3}{3T(2M_b + M_c L_c)} \tag{50}$$

where

D_c deflection of the curtain (m);
ρ_0 density of ambient air (kgm^{-3});
θ temperature rise above ambient of the gases in the smoke layer (°C);
d depth of the gas layer (m);
M_b weight per metre length of the curtain's bottom bar (kgm^{-1});
M_c weight per m^2 of the curtain fabric (kgm^{-2});
L_c length of the smoke curtain from top to bottom bar, measured along the fabric (m).

The length of the curtain to contain a gas layer of depth d can be calculated using an iterative procedure from:

$$L_c = d + D_c \tan\left[\frac{\tan^{-1}\left(\frac{D_c}{d}\right)}{2}\right] \tag{51}$$

The procedure is as follows:

1) Assume a starting value for $L_c \geq d$.
2) Calculate D_c using equation (50).
3) Calculate next value of L_c using equation (51).

Repeat steps 1) to 3) with the new value of L_c, until successive values of L_c differ by an acceptably small amount (e.g. 1 %).

The calculated value for L_c can then be modified by including a term to allow for bowing of the curtain, so that [5]:

$$L_{c(\text{final})} = L_c + 1.7(L_c - d) \tag{52}$$

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9.10.3 *Curtains closing an opening*

The deflection of a curtain that is used to completely close an opening where the smoke layer extends below the bottom of the curtain is [5]:

$$d_c = 1.2\frac{\rho_0\theta(3d - 2h)h^2}{3T(2M_b + M_c L_c)} \tag{53}$$

where

h is the height of the opening (m) and other variables are as defined above.

The required curtain length is calculated using a similar iterative procedure but using equations (53) and (54) instead of (50) and (51):

$$L_c = h + D_c \tan\left[\frac{\tan^{-1}\left(\frac{D_c}{h}\right)}{2}\right] \tag{54}$$

Again the calculated value for L_c must then be modified by including a term to allow for bowing of the curtain as for curtains not reaching the floor, so that:

$$L_{c(\text{final})} = L_c + 1.7(L_c - h) \tag{55}$$

10 Fire safety management

Once installed it is essential that the smoke control system along with other passive and active fire safety systems are working properly. BS 9999-4 describes how by careful consideration during the design phase, the fire safety manager can ensure that all functions are conducted effectively. It describes the frequency of inspection, maintenance and testing of the fire safety systems.

11 Data

Table 1, Table 2 and Table 3 show the fraction of chemical heat release from some materials convected by plume in well-ventilated fires and fire products from well-ventilated flaming combustion of specified products respectively.

Table 1 — Fraction of chemical heat release from some materials convected by plume in well-ventilated fires (Tewarson [36])

Material	Convected fraction
ethanol	0.74
kerosene	0.65
benzene	0.40
octane	0.67
silicone	0.84
PMMA	0.69
Douglas fir	0.62
polystyrene	0.41
polyurethane	0.42

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Table 2 — Fire products from well-ventilated flaming combustion of generic products from Tewarson [36] and Mulholland [37]

Material	Carbon Monoxide, Y_{CO} (kg/kg)	Mass optical density, D_m (m^2/kg)
Cellulosics	0.004	400
Plastics	0.024 to 0.063	240 to 1 000
Generic building contents	0.013	300

NOTE CO yield in particular will rise substantially with less well-ventilated combustion and can be expected to reach 0.25 for most products in such conditions.

Table 3 — Fire products from well ventilated flaming combustion from Tewarson [36] and Mulholland [37]

Material	Carbon Monoxide yield, Y_{CO} (kg/kg)	Mass optical density, D_m (m^2/kg)
plywood	—	290
PMMA	0.010	150
PVC (with plasticizer)	0.063	640
Douglas fir	0.004	280
polystyrene	0.060	790 to 1 400
polyurethane	0.024	220 to 330
ethanol	0.001	—
kerosene	0.012	—
benzene	0.067	—
octane	0.011	—
silicone	0.006	—

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Annex A (informative)
Computer modelling

A.1 Model types

Two model-building strategies have evolved for calculating the effects of fire in enclosures. They differ primarily in their treatments of the gas phase. The more traditional method relies on assembling a relatively small number of constituent equations, each of which describe, to the desired level of accuracy, a recognized "component" of the overall system. Typical components might be any of those listed in the main text. Typically they are a thermal plume rising above the fire source, a distinct ceiling layer of hot combustion products which then flows out through an "inverted" weir above an open window or through a doorway to an adjacent space (Figure A.1).

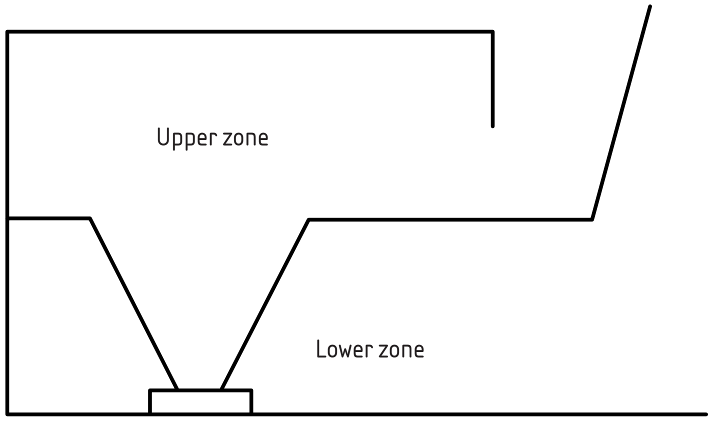

Figure A.1 — Schematic representation of a computer zone model

Such zone models, as they have become known, are based largely on *a priori* assumptions, guided by experience and observation, on how fires develop. The most important of these is that the enclosure of concern fills with smoke in the same but inverted manner of a bathtub filling with water. The smoke is thus assumed to immediately form a layer beneath the ceiling and to fill downwards uniformly across the entire expanse of the ceiling. Whether a zonal treatment can be exploited will depend largely on whether this assumption is valid for the particular design under consideration. The advantage that the computer zone model has when compared with the individual equations listed in Clause **9** is the ability to run a fully coupled transient calculation and to calculate the filling of an enclosure with time. It is also straightforward to include the effects of heat loss to the bounding surfaces.

The more recent method, exploiting techniques widely used elsewhere in engineering fluid mechanics, is to solve directly throughout the domain of interest, using numerical methods, the three dimensional, time-dependent equations describing the laws of conservation subject to the particular boundary conditions of the problem (Figure A.2). These models, sometimes referred to as field models, and based on the application of computational fluid dynamics (CFD), have only become a possible alternative to the zonal approach because of the rapid advances in recent years in the development of electronic computers. Their viability is critically dependent on the speed and memory of modern computer "hardware". They are more complex and expensive to run than the zonal models but are, in principle, more universally applicable.

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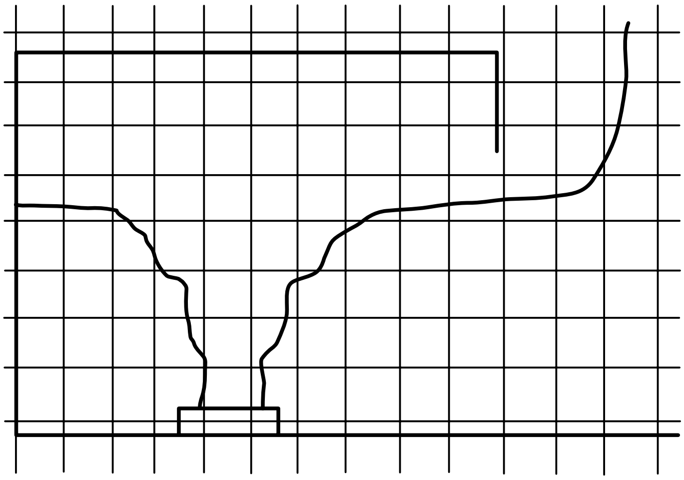

Figure A.2 — Schematic representation of a CFD model

Greater emphasis is given here to the CFD models since much of the zonal modelling treatment is covered by Clause **9**.

A.2 Zone models

The concept of the zone model is to characterize the enclosure fire by a series of separable component processes, or zones, that go together to describe the system as a whole. Each zone is considered in isolation and is described by global, semi-empirical equations such as those listed in Clause **9** and deduced usually from dimensional reasoning with proportionality constants supplied by experiment. Indeed the zone model may be regarded as simply a synthesis of selected estimating formulae either presented above or accepted as reasonable alternatives. The computer merely facilitates rapid calculation and interaction in a transient manner between zones that is difficult when moving sequentially through the component equations of Clause **9**.

The treatment for the thermal plume above the fire source might be equation (2) for example, with influence of the enclosure on the plume ignored. However it is important to realize that most zone models have been developed from research programmes and that the individual equations exploited can differ from those listed here and indeed differ between models. It is thus very important for the user to be aware of the constituent parts of the models available and to be in a position, not only to decide whether the zonal assumptions are valid, but also to select the zone model appropriate for the particular application.

The theoretical basis of this approach to modelling has been discussed in some detail elsewhere, e.g. [38], [39] and descriptions of selected models will be found, for example, in [40], [41] and [42].

Clearly the important zones will differ from one class of problem to another. Yet most existing models have been constructed with the purpose of treating a single compartment or series of compartments whose size is representative of domestic rooms, offices or smaller industrial units. For these it may be perfectly reasonable to assume, for example, that smoke fills the compartment from top to bottom in a mirror image of how water from a tap fills a bathtub-essentially stagnant and one-dimensional. However, of course, for much larger compartments such as tall atria or those with a very large expanse of ceiling, such an assumption may not be valid.

The plume rise in a tall volume is dependent upon the ambient levels of temperature stratification-see equations (13) and (14). There will be a fire size for a given level of stratification below which its combustion products may never reach the ceiling or at least will be delayed significantly before doing so. In a large area building, where the combustion products do reach the ceiling, they can take a substantial time to reach the bounding walls and indeed can cool sufficiently to mix with lower ambient air currents. Such possibilities require special attention when using and interpreting the results from a zone model.

Although the modern digital computer is not essential to the use of zonal models, its application permits far more zones to interact than would otherwise be possible.

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A.3 Computational fluid dynamics (CFD)

A.3.1 *General*

Since its emergence as a practical design and analysis tool, computational fluid dynamics has made an increasingly significant contribution to the solution of fluid flow problems in many branches of engineering. Examples of its application can be found in many areas ranging from airframe, ships' hull and car body design through to analyses of the efficiency of gas turbines, cement kilns and glass furnaces. It is also being used for the design of heating and ventilation systems in buildings [42].

The models solve, numerically, the partial differential equation set describing the principles of local conservation of mass, momentum, energy and species, subject to the particular boundary conditions of the problem [38]. They provide calculations of hazard from a developing fire without making the assumptions necessary in more traditional analyses. For example, it is not necessary to assume, as do the zone models, that the smoke from a fire will instantaneously cover the ceiling of a compartment in the form of a homogeneous layer and then fill it from the top downwards. The influences of pre-fire ambient stratification that may distort this simple picture, at least in the early stages, can be taken into account. Similarly the transit of the ceiling jet over a large ceiling can be examined, as can the influences on plume air entrainment caused by the presence of walls and fire-induced winds. These effects are all incorporated naturally by the more fundamental approach of CFD. It is not necessary to assume that plume entrainment is described by, for example, equations (2) or (8); instead it will be determined during the solution of the underlying equations. Furthermore the influences of external wind forces, difficult to account for in the zonal treatment, are taken account of through choice of appropriate boundary conditions.

A.3.2 *Principles*

Only a brief summary of the methodology is offered here, more details will be found elsewhere [39], [44], [45].

CFD models start with the "exact" instantaneous partial differential equation set describing the local conservation principles. For smoke movement problems these are then solved subject to the following critical decisions:

a) how to treat the problem of turbulent mixing;

b) which algorithm is to be used to calculate the numerical solution of the resulting equations at interior points of the flow domain;

c) how properly to approximate boundary conditions along the domain boundaries;

d) how to treat combustion and thermal radiation.

In the decision a) above, most practical applications of CFD to date have exploited a time-averaged approach to solving the "exact" equations and this is what will be presented here. However an alternative approach using large eddy simulation techniques has become a viable alternative for application to smoke movement problems but as yet the degree of verification is less than for the procedure outlined here. More information on this approach can be found in [46].

The basic equation set for the simulation of fires in enclosures comprises time-averaged conservation equations for mass, momentum, energy and chemical species of the general form:

$$\frac{\delta}{\delta t}(\rho\phi) + \frac{\delta}{\delta x_j}(\rho u_j \phi) = \frac{\delta}{\delta x_j}\left(\Gamma_\varphi \frac{\delta \phi}{\delta x_j}\right) + S_\varphi \qquad \text{(A.1)}$$

i.e. time
rate of + Convection = Diffusion + Source/Sink
change

where ϕ is a generic variable that may represent, for example, the three Cartesian velocity components u_i, the enthalpy h or the mass fraction of a particular species Y_i. (The mass continuity equation is represented by the case $\phi = 1$.) S_φ is a source term appropriate to ϕ which incorporates, for example, the effects of chemical production and radiative heat loss.

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A Cartesian grid is not essential but is assumed here for simplicity. All dependent variables in equation (A.1) are time averaged quantities and, since density fluctuations are usually neglected, may be viewed as implicitly density-weighted, for example:

$$u_{\mathrm{i}} = \frac{\overline{\rho u_{\mathrm{i}}}}{\bar{\rho}} \tag{A.2}$$

The diffusion term incorporates the effects of both turbulent and molecular diffusion through the exchange coefficient Γ_{φ}. In most field models it is assumed that the Reynolds stresses and scalar fluxes, which involve the correlations of fluctuating properties, can be modelled by use of the gradient transport hypothesis, which for scalars is:

$$\bar{\rho} \cdot \overline{u_{\mathrm{i}}' \phi'} = -\Gamma_{\varphi} \frac{\delta \bar{\phi}}{\delta x_{\mathrm{i}}} \tag{A.3}$$

Here u_{i}', and ϕ'represent the fluctuating components of velocity and the generic variable respectively.

To determine the local value of Γ_{φ} two further transport equations are solved for k, the turbulence kinetic energy and its rate of dissipation, ε. The effects of buoyancy on extra turbulence production (in rising plumes) and inhibition (in stratified layers) require special attention.

The modelled conservation equations are then discretized and solved iteratively on a numerical grid of hundreds of thousands, maybe millions of elementary control volumes filling the computational domain. This is achieved using "guess-and-correct operations".

Solution of these equations alone, together with the appropriate initial and boundary conditions is sufficient to capture the major features of the smoke movement problem for a known fire size.

However the incorporation of a combustion model is extremely important for modelling the extended release of heat over a volume determined by local mixing conditions. The temptation to represent the fire by a heat source should be resisted without a clear appreciation of the consequences.

Where it is necessary to estimate hazard to human life due to inhalation of toxic gases or to radiative and convective heat exposure the "sub-models" of combustion and thermal radiation are also needed.

A.3.3 *Combustion*

The treatment of the effects of turbulent transport has already been mentioned briefly. Unfortunately the turbulent mixing process also has a significant influence on the mean rate of chemical reaction. The hydrodynamic mixing of fuel with air is much slower in fires than is the rate of chemical reaction and so it is the former which controls the rate of fuel disappearance, R_{fu}, and of product yield.

A simple method for dealing with this difficulty is to allow the combustion process to be controlled only by the rate of small-scale turbulent mixing between the reactants and for that rate to be further controlled by the concentration of deficient reactant (either air or fuel). In air-rich locations, the reaction is controlled by lack of fuel and vice-versa in fuel-rich locations, thus:

$$R_{\mathrm{fu}} = -C\rho\frac{\varepsilon}{k}\min\left\{Y_{\mathrm{fu}}\frac{Y_{\mathrm{ox}}}{s}, Y_{\mathrm{fu}}Y_{\mathrm{ox}}B\ \exp\left(\frac{-E}{RT}\right)\right\} \tag{A.4}$$

where

Y_{fu}, Y_{ox} are the local mass fractions of fuel and air;
s is the stoichiometric ratio;
C is a numerical constant;
E is the activation energy;
R is the gas constant.

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A transport equation for Y_{fu}, incorporating the above source term, is solved in addition to one for a normalised mixture fraction, *f*; where:

$$f = \frac{\left(Y_{\text{fu}} - \frac{Y_{\text{ox}}}{s}\right) + \frac{Y_{\text{ox},\infty}}{s}}{Y_{\text{fu},0} + \frac{Y_{\text{ox},\infty}}{s}} \tag{A.5}$$

Since *f* is conserved its transport equation does not involve a source term. [The subscripts (0, ∞) denote conditions in the fuel supply and ambient air respectively]. This method can be used to predict the major features of a wide range of building fire problems including the stable species of CO_2 and H_2O.

A.3.4 *Thermal radiation*

Two quite distinct difficulties need to be addressed for the realistic modelling of radiant heat transfer. The first concerns "geometrical" problems associated in particular with the exchange of radiant energy between remote emitters and receivers, be they solid surfaces such as compartment walls or particulate/gas phase mixtures such as smoke and flames. The second difficulty concerns the calculation of the local emissive power. The relative contributions from soot and gaseous emissions will vary substantially between flame and smoke products. In addition, as with transport processes and combustion chemistry, the effect of turbulent fluctuations in temperature and gas composition may influence radiant heat transfer. In smoke movement assessment this latter influence is generally ignored. Many smoke movement analyses assume a grey gas of fixed absorptivity and calculate radiant heat transfer only in the six Cartesian coordinate directions based on time-mean predictions of local gas temperature.

A.3.5 *Heat transfer between smoke and enclosure surfaces*

Solution of the enthalpy transport and radiative transfer equations describes the internal processes of heat redistribution with the building enclosure but heat is also lost into the enveloping structure. A similar treatment to that adopted in zone modelling can be exploited by solving a quasi-steady, one-dimensional conduction equation for every control volume on the enclosure boundaries. The heat flux per unit area lost by conduction, q''_{cond} to the boundaries is:

$$q''_{\text{cond}} = -k_{\text{w}} \frac{T_{\text{s}} - T_0}{\delta} \tag{A.6}$$

where the temperature gradient within the solid is assumed here to be linear between the internal surface at T_{s} and a thermal penetration depth, δ, which is time dependent:

$$\delta = \frac{2}{\sqrt{\pi}}\left(\frac{k_{\text{w}} t}{\rho_{\text{c}} C_{\text{w}}}\right)^{1/2} \tag{A.7}$$

where

k_{w}	is the thermal conductivity of the bounding solid;
ρ_{c}	is the density of the bounding solid;
C_{w}	is the specific heat of the bounding solid;
t	is the thermal penetration time.

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A.3.6 *What the models predict*

The primary output of this kind of model is a series of time histories for each of the variables solved in the equation set A.1 (i.e. gas velocities, gas temperatures, fuel, oxidant and combustion product concentrations together with pressures) at each elementary control volume throughout the calculation domain. Mass fluxes through ventilation openings as well as convective and radiative heat fluxes across the face of solid boundaries are also provided.

Secondary variables can be deduced from the primary ones by the use of further assumptions. Smoke obscuration in each control volume, for example, can be deduced from local combustion product concentration, as can concentrations of detailed chemical species. However, deductions of these secondary variables are heavily dependent on the assumptions made and are in the spirit of the zonal modelling approach. The validity of these assumptions should always be kept under review.

A.3.7 *What assumptions are necessary?*

As has been mentioned, models of this type avoid many of the assumptions implicit in the construction of a zonal model. However, as with models of all types, CFD models also rely on assumptions regarding the choice of design fire. The state of development of fire science is, as yet, unable to make accurate a priori predictions of fire growth for practical situations. For design purposes it is necessary to resort to assumed fire growth curves of the type described in Sub-system 1 (PD 7974-1).

A.3.8 *Numerical treatment*

It is not the intention of this annex to consider the details of the numerical treatment, however the implications of using such a method need to be appreciated.

a) The computer solutions are discretized approximations to the continuous partial differential equation (A.1), calculated at the grid points of a numerical mesh spanning the domain of interest. The variation of property between grid points has to be assumed.

b) The discrete nature of the solution means that it cannot accurately capture all the physical features of the true solution at length or time scales less than those associated with the numerical mesh and time step. Cell dimensions are typically quite large, often greater than 0.1 m, and, particularly in large compartments, usually substantially larger, i.e. perhaps even several metres. Phenomena at smaller length scale are described by approximate “sub-grid” scale turbulence modelling.

A.3.9 *Acceptance of the solution*

Before any engineering judgement is made on a numerical solution it is important that an acceptable level of convergence be demonstrated. Convergence is the term that describes whether or not the solutions of the discretized form of the equations approach the true solution of the partial differential equations having the same initial and boundary conditions, as the numerical mesh is refined and as the number of numerical iterations increases. Since the true solution is not known, convergence is determined for a given mesh from inspection of the behaviour of the “residual” errors in each of the conservation equations as iterative solutions proceed.

These residual errors are the magnitudes of imbalance between right- and left-hand sides of the discretized equations using the latest solution of the “guess-and-correct” operation for each variable. It is not enough simply to demonstrate that a solution does not change as iteration proceeds. This could occur if considerable under-relaxation has been used in an attempt to procure convergence and the solution then becomes frozen but not converged. Furthermore it is important to examine the sensitivity of the solution to grid refinement. This can be an expensive task; refining a grid by a factor of two in each co-ordinate direction will increase computational cost roughly by a factor of eight so it is often necessary to strike a compromise between cost and accuracy. Most CFD packages provide diagnostic information on the progress of residual errors for each of the equations solved. However, it is important to be satisfied that overall mass and energy balances for the whole domain are within acceptable bounds. Compartment mass outflows should balance mass inflows and heat lost into the structure taken together with heat lost from the compartment through its openings should balance that generated by the fire.

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There will be occasions where the model can suggest unexpected behaviour. If a physical simulation were to produce something unexpected, the engineer would use his or her knowledge and experience to explain what has been seen or what has been measured and to relate it to the practical problem in hand. However, with a numerical simulation such an eventuality is more disturbing since it can have two explanations; either it is genuine and would have been observed in a physical simulation or alternatively it is some sort of misleading numerical artifact.

The possibility of the latter cannot be completely discounted with such complex numerical simulations as those involved in CFD. It is therefore essential to "shadow" the numerical simulation, where possible, with known simple calculation methods.

A.3.10 *Mode of working*

Since computational fluid dynamics is a particularly complex undertaking its practitioners can be specialists with little experience in fire science and fire engineering. Therefore, when applying CFD to fire problems, it is particularly important that the project team contain both fire and CFD skills to ensure that the problem is properly posed and that the results produced are reasonable.

The responsibilities of the fire engineer and CFD practitioner can be summarized as follows.

The fire engineer needs to:

a) simplify the problem to its essentials; the presence of design features can influence some aspects of a problem but not others, e.g. structural beams that can significantly affect detection times but not smoke filling times;

b) specify the way that the fire source is to be treated (constant or growing fire) and decide in discussion with the CFD practitioner whether the fire is to be treated simply as a heat source of known volume or area or whether a combustion sub-model is required;

c) "shadow" the CFD simulations with simple calculations such as those presented in this document and the other PD's to determine whether the results obtained from the CFD are reasonable.

The CFD practitioner needs to:

1) decide on the placement and refinement of the grid mesh in discussion with fire safety engineer (to determine where steep property gradients are expected etc.) and the time step size;

2) demonstrate convergence, energy and mass balance information;

3) provide a statement on the degree to which grid insensitive solutions have been obtained;

4) set down the assumptions on which any "secondary" variables such as visibility or gas species concentration are based.

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Annex B (informative) Indicative calculation procedure

Figure B.1, Figure B.2, Figure B.3, Figure B.4 and Figure B.5 show smoke spread in various situations, for calculation purposes.

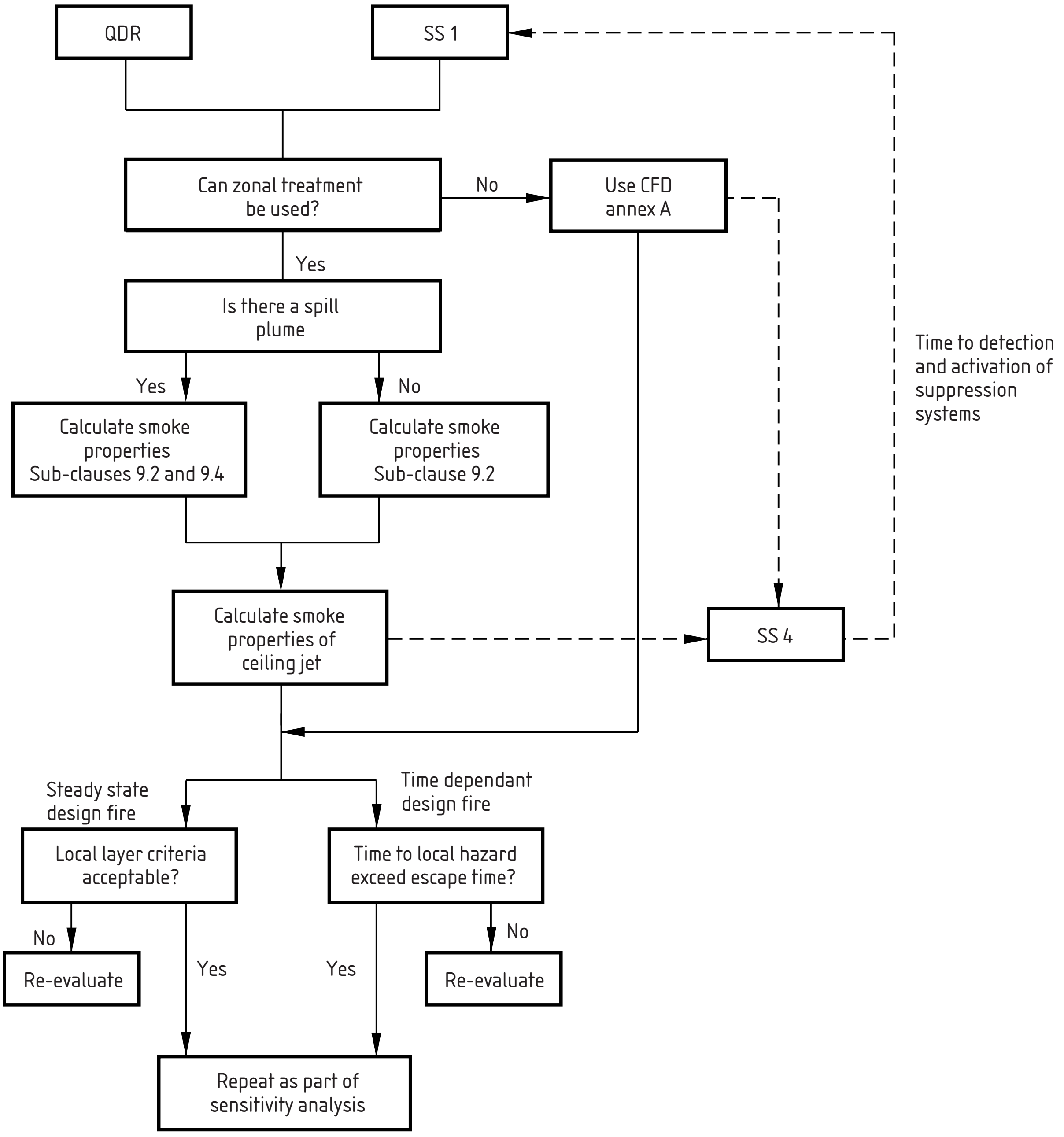

Figure B.1 — Flow chart

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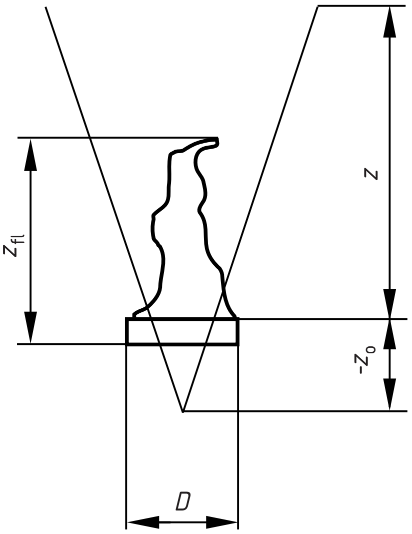

Figure B.2 — Schematic showing location of virtual origin for calculation of smoke mass flow rate in “far field

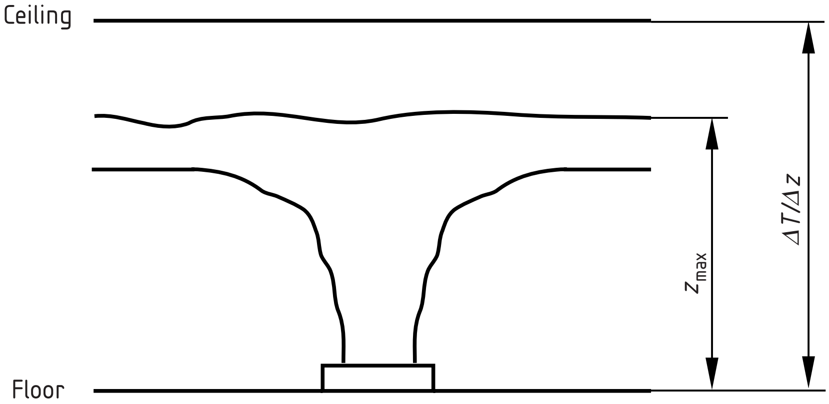

Figure B.3 — Schematic showing smoke stratifying before reaching ceiling in an ambient environment where air temperature is elevated at ceiling level

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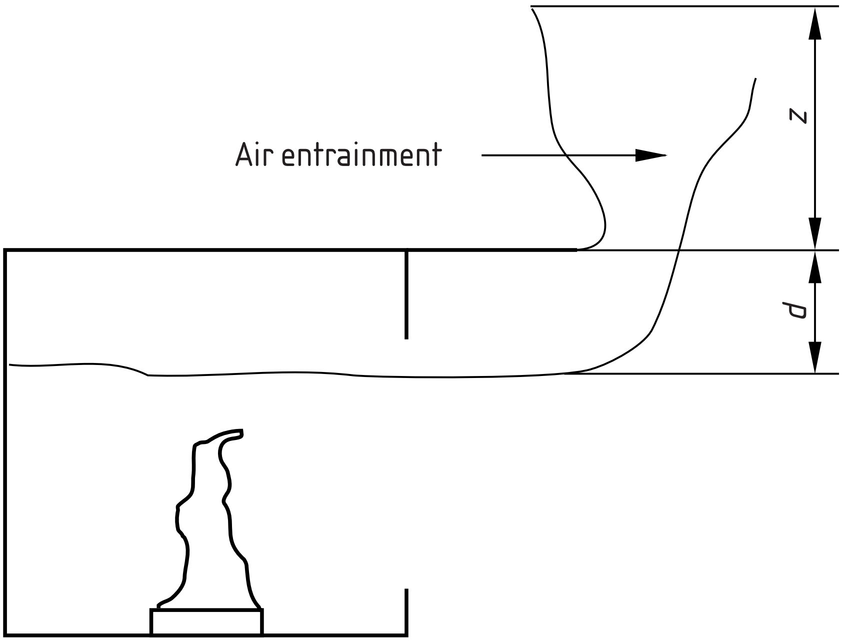

Figure B.4 — Side elevation of smoke layer spilling over balcony edge

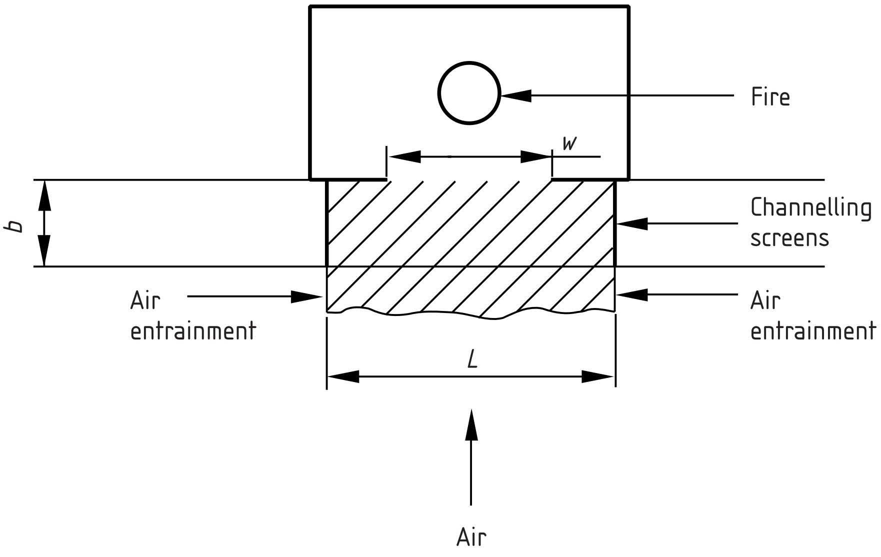

Figure B.5 — Plan view of smoke channelled by screens

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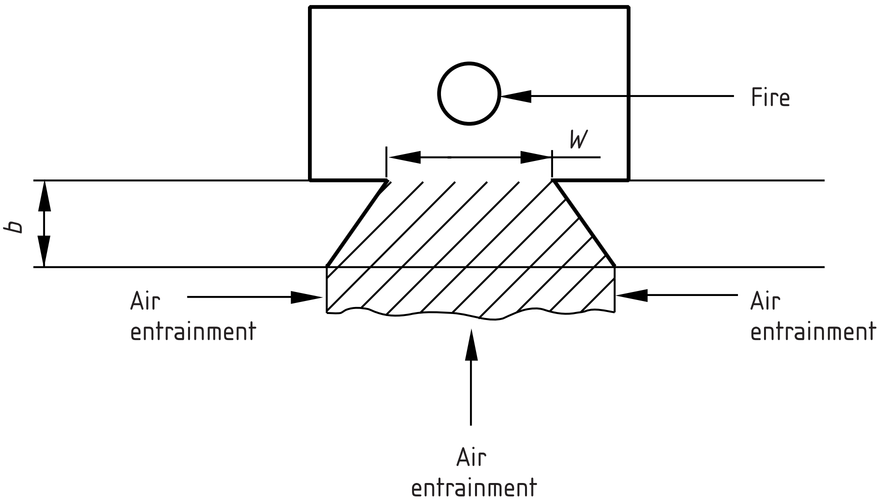

Figure B.6 — Plan view of smoke spreading unchannelled beneath balcony

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