



BSI Standards Publication

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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Foreword

Publishing information

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

Supersession

This Published Document supersedes PD 7974-2:2002, which is withdrawn.

Relationship with other publications

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

Other documents in the series are:

PD 7974-1: *Initiation and development of fire within the enclosure of origin*;

PD 7974-3: *Structural response to fire and fire spread beyond the enclosure of origin* ;

PD 7974-4: *Detection of fire and activation of fire suppression systems*;

PD 7974-5: *Fire service intervention*;

PD 7974-6: *Evacuation*;

PD 7974-7: *Probabilistic risk assessment*;

Where appropriate, references to relevant standards are provided in order to assist the reader in understanding the design methodologies presented and to compare different approaches or sources of data. It is therefore important that PD 7974-2 is not used in isolation and reference is made to the relevant standards, particularly in relation to additional notes and subclauses describing its application.

Information about this document

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

- greater clarity regarding smoke control design principles, application and procedures;
- new information on the practical application of natural and mechanical smoke control, and the use of smoke barriers;
- rationalization of guidance on computer simulation modelling principles, as the intent of this guide is smoke control rather than computer fire modelling;
- where practicable, explicit acknowledgements of the inherent assumptions and limitations of underpinning design correlations;
- revised and new correlations with respect to spill plumes and the axisymmetric plume;
- new figures to aid the correct use of design correlations;
- calculation of smoke detection time for activating smoke control;
- greater clarity on design considerations for smoke reservoir size, and the interaction between sprinklers/smoke ventilation; and

- improved reference data for smoke and toxic gas yields.

Use of this document

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

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

Presentational conventions

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

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

Contractual and legal considerations

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

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

0 Introduction

This Published Document (PD) is one of a series of documents intended to support [BS 7974](#). It 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.

This PD contains guidance and information on how to undertake quantitative analysis for smoke control. This PD is a summary of the latest knowledge and techniques and it does not preclude the use of appropriate methods and data from other sources.

When used by suitably qualified persons, experienced in fire safety engineering, this PD provides a means of establishing acceptable levels of fire safety economically and without imposing unsuitable constraints on aspects of building design.

Sub-system 1 (see 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 PD forms part of a series of Sub-systems 1 to 6 (see PD 7974-1 to PD 7974-6), but may, in consultation with the appropriate references, be regarded as “stand-alone” guidance.

PD 7974-4 has now been withdrawn; it provided guidance on the detection of fire and activation of fire protection systems. This guidance is now included in the various parts of the PD 7974 series and other standards covering the subject. PD 7974-4 is referred to as part of the PD 7974 series for the sake of completeness but is no longer maintained as a current document.

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.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and symbols

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

3.1 Terms and definitions

3.1.1 aerodynamic free area

product of the geometric area and the discharge coefficient

[SOURCE: BS 7346-4:2003, 3.1.2]

3.1.2 air entrainment

mixing of ambient air into a jet or plume

3.1.3 ambient condition

property of the surroundings outside the influence of a fire

3.1.4 axisymmetric plume

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

3.1.5 ceiling jet

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

3.1.6 channelling screen

fixed or moveable smoke barrier to control lateral spread and channel smoke, typically fitted beneath a balcony

3.1.7 compartment

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

3.1.8 computational fluid dynamics (CFD) model

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

3.1.9 convective heat output

total heat energy carried by the gases crossing a specified boundary per unit time

3.1.10 design fire

hypothetical fire having characteristics to serve as the basis of design

[SOURCE: BS 7346-4:2003, 3.1.14]

3.1.11 discharge coefficient

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

3.1.12 discretize

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

3.1.13 enclosure

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

3.1.14 fire detection

detection of a fire by occupants and/or mechanical device

3.1.15 fire safety engineering

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

3.1.16 flashover

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

[SOURCE: BS 7974:2019, 3.21]

3.1.17 geometric free area

area of the opening through a ventilator, measured in the plane defined by the surface of the building, where it contacts the structure of the ventilator

NOTE No reduction is made for controls, louvres or other obstructions.

3.1.18 natural smoke control

ventilation resulting from non-mechanical means or the exploitation of the thermal buoyancy of the smoky gases to exhaust them to be replaced at inlets by ambient air

3.1.19 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

3.1.20 replacement air

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

3.1.21 sensitivity analysis

calculation of rate of change of output as a function of rate of change of an input parameter of input

3.1.22 smoke barrier

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

3.1.23 smoke reservoir

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

3.1.24 spill edge

horizontal edge of a fire compartment opening or balcony when an initially horizontal moving smoke layer rises vertically as a plume into an open void space

3.1.25 spill plume

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

3.1.26 tenable conditions

maximum exposure to hazards from a fire that can be tolerated without violating safety goals

3.1.27 virtual source

point or line from which a plume appears to have emerged

3.1.28 visibility distance

maximum distance at which an object of defined size, brightness and contrast can be seen and recognized

3.1.29 zone model

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

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

3.2 Symbols

$\varepsilon_{\text{smoke}}$	smoke particulate (soot) yield (or mass conversion factor) (kg particulates/kg fuel mass loss)
k	a buoyancy coefficient ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-5/2}$)
κ_{m}	a profile correction factor (dimensionless)
ρ_0	ambient air density ($\text{kg}\cdot\text{m}^{-3}$)
ρ_i	density of the species i ($\text{kg}\cdot\text{m}^{-3}$)
η	constant
$\bar{\theta}$	mass weighted average excess temperature ($^{\circ}\text{C}$)
θ_{a}	temperature rise necessary to trigger an alarm ($^{\circ}\text{C}$)
θ_{cj}	maximum temperature rise in the ceiling jet ($^{\circ}\text{C}$)
$\bar{\theta}_{\text{cl}}$	mean centreline excess gas temperature rise in an axisymmetric plume ($^{\circ}\text{C}$)
θ_{imp}	maximum temperature rise in the vertical plume at the impingement point ($^{\circ}\text{C}$)
θ_1	excess temperature of the smoke layer in a reservoir ($^{\circ}\text{C}$)
θ_{max}	maximum temperature rise in the hot gas layer at the opening ($^{\circ}\text{C}$)
φ	equivalence ratio of air to volatiles
τ	detector time constant (s)
X	fraction of the total heat release convected by the plume (dimensionless)
A_{in}	total area of all inlets (m^2)
A_{v}	throat area of the ventilator (m^2)
A_{SEA}	specific extinction area ($\text{m}^2\cdot\text{kg}^{-1}$)
b	horizontal distance from the compartment opening to balcony/soffit edge (m)
c_i	mass concentration of species i ($\text{kg}\cdot\text{m}^{-3}$)
C_{d}	discharge coefficient for the opening (dimensionless)
C_{e}	constant of proportionality in equation (12) ($\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-5/2}$)
C_i	volume concentration of species i (dimensionless)
C_{in}	entry coefficient for inlets (dimensionless)
$C_{\text{p},0}$	specific heat of air at constant pressure ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
c_{s}	smoke particulate mass concentration ($\text{g}\cdot\text{m}^{-3}$)
C_{v}	coefficient of discharge (dimensionless)
d_{c}	deflection of a smoke curtain, measured at its bottom bar (m)

d_l	smoke layer depth in a reservoir (m)
d_s	smoke layer depth below the spill edge (m)
d_o	smoke layer depth below the fire compartment opening (m)
d_v	depth of smoke below centreline of vent (i.e. to mid vent)
d	smoke layer depth in the opening (m)
D	optical density per unit path length of the smoke (m^{-1})
D_a	optical density per unit path length of the smoke necessary to trigger an alarm (m^{-1})
D_c	deflection of the curtain (m)
D_m	mass optical density for the fuel concerned ($\text{m}^2 \cdot \text{kg}^{-1}$)
D_s	source diameter or characteristic length (e.g. longer linear dimension for a line fire) (m)
E	entrainment coefficient
f_b	total mass of fuel burnt (kg)
g	acceleration due to gravity ($\text{m} \cdot \text{s}^{-2}$)
h	height of opening (m)
h_o	height of the top of the fire compartment opening above the level of the fire (m)
h_s	height of the spill edge above the level of the fire (m)
H_a	height of smoke contamination of upper balconies above the spill edge in an atrium (m)
I	light intensity distance, s , from an observed object of intensity I_0
K	light extinction coefficient (m^{-1})
K_m	specific extinction coefficient ($\text{m}^2 \cdot \text{g}^{-1}$)
l	corridor half width (m)
L	pathlength (m)
L_c	length of the smoke curtain measured along the fabric (m)
L_d	characteristic length (m)
$\dot{m}_{\text{crit}}$	critical mass flow rate of an exhaust point prior to plugholing ($\text{kg} \cdot \text{s}^{-1}$)
$\dot{m}_{\text{fuel}}$	mass burning rate of fuel ($\text{kg} \cdot \text{s}^{-1}$)
$\dot{m}_{\text{smoke}}$	mass flow rate of smoke ($\text{kg} \cdot \text{s}^{-1}$)
$\dot{m}_O$	mass flow rate of smoke below the fire compartment opening ($\text{kg} \cdot \text{s}^{-1}$)
$\dot{m}_S$	mass flow rate of smoke below the spill edge ($\text{kg} \cdot \text{s}^{-1}$)
M_b	weight per unit length of the curtain's bottom bar ($\text{kg} \cdot \text{m}^{-1}$)
M_c	weight per unit area of the curtain fabric ($\text{kg} \cdot \text{m}^{-2}$)
n	a constant in equation (35) (dimensionless)

N	number of extract vents (dimensionless)
p	perimeter of the source (m)
$\dot{Q}_c$	rate of heat release convected by the plume (kW)
$\dot{Q}$	total rate of heat release of the fire source (kW)
$\dot{Q}''$	total rate of heat release per unit area of fire source (kW·m ⁻²)
r	radial distance from the ceiling impingement point (m)
s	optical path length (m)
S	visibility distance (m)
t_b	duration of fully developed burning (s)
T	local smoke temperature (K)
T_l	absolute temperature of gas layer in a reservoir (K)
$T_{\max}$	maximum temperature in the hot gas layer at the opening (K)
T_0	ambient air temperature (K)
u_{cj}	maximum gas velocity in the ceiling jet (m·s ⁻¹)
u_{cjd}	ceiling jet velocity flowing past the detector (m·s ⁻¹)
$\bar{u}_{cl}$	mean centreline gas velocity in an axisymmetric plume (m·s ⁻¹)
$\dot{V}$	volume flow rate of smoke (m ³ ·s ⁻¹)
V_t	total volume of smoke at a location (m ³)
w	width of the opening (m)
W_o	width of the flow at the fire compartment opening (m)
W_s	width of the flow at the spill edge (m)
w_v	characteristic width of the ventilator (m)
y	distance along the corridor from the impingement point (m)
Y_i	mass yield of the species i (kg·kg ⁻¹)
z	height above the fuel surface (m)
z_o	height of the virtual source above or below the fuel surface (m)
z_f	mean height of visible flames above the fuel surface (m)
z_H	height of the ceiling above the fire source (m)
$z_{\max}$	maximum height of rise of smoke plume (m)
z_s	height of rise from the spill edge to the underside of the smoke layer over which entrainment can occur (m)

z_{trans} height of rise from the spill edge to the underside of the smoke layer when the plume flow becomes axisymmetric in nature (m)

4 Design considerations

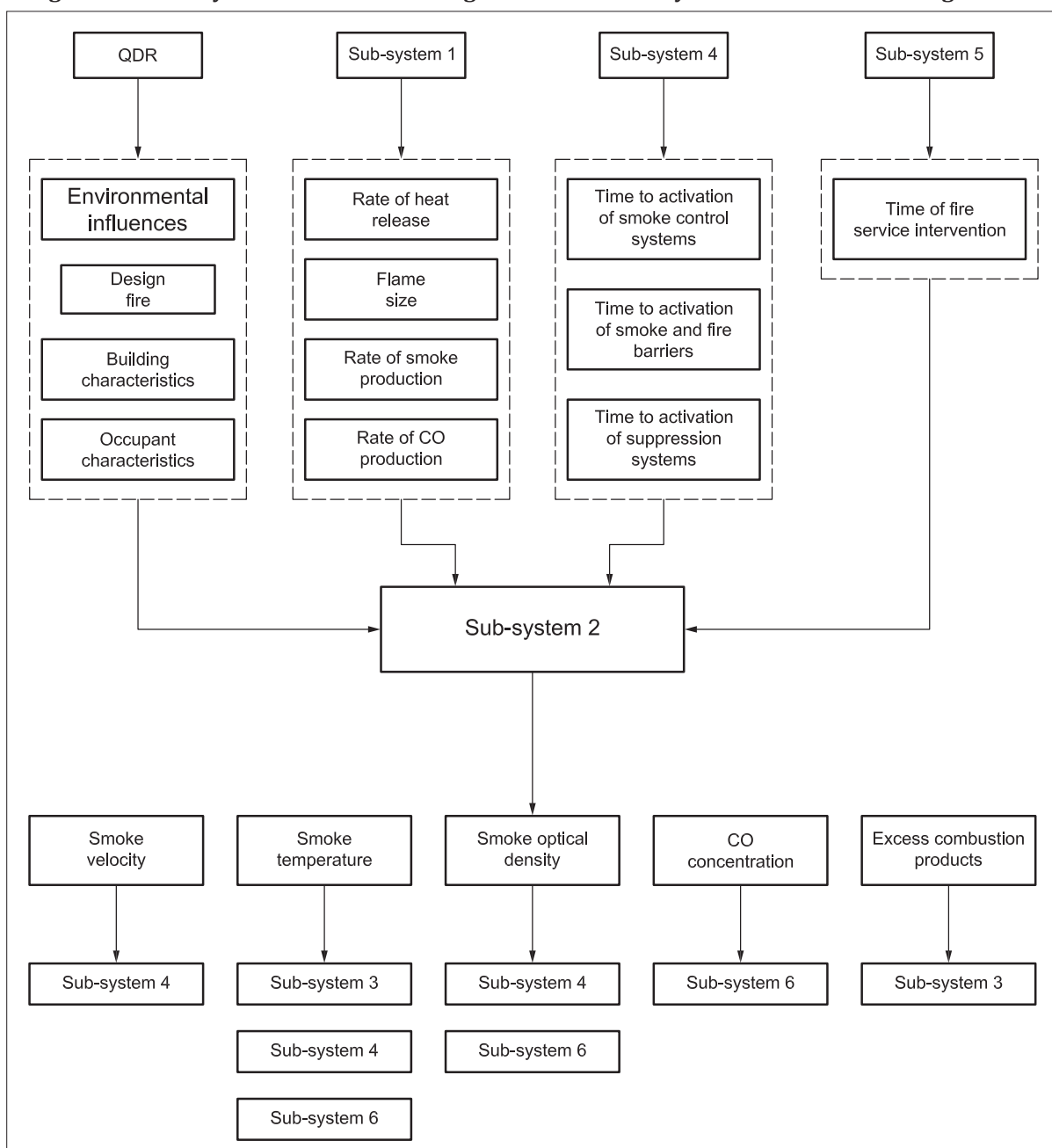
COMMENTARY ON CLAUSE 4

The design considerations provided in this clause assist the team during the Qualitative Design Review (QDR) process, detailed in BS 7974, but do not cover all potential smoke control issues to be considered.

Refer to BS 7974 with regards to competency and qualifications of both designers and reviewers.

4.1 Identify relationship between sub-systems

It might 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), however there is likely to be substantial interdependence between sub-systems (see [Figure 1](#)).

Figure 1 — Stages for the analysis of smoke and toxic gases within and beyond the enclosure of origin

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

4.2 Review limitations and sensitivity

The calculation methods and data contained in this PD are included with the known limitations. Alternative data and calculation methods are not precluded and might be required. Satisfactory justification of any calculation method or approach selected should always be provided.

It is recommended that a sensitivity analysis be conducted to examine the consequences of the choices made for smoke control and for the 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, providing a degree of redundancy to the design should be taken into account.

It is important to appreciate that what might be conservative for one component of the design could 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.

4.3 Confirm appropriate applications

COMMENTARY ON 4.3

The four typical applications, which are not exclusive, for smoke control systems are given in 4.3.1 to 4.3.4.

4.3.1 Protection of means of escape

Achieving tenable conditions within a means of escape route can be undertaken in a number of different ways including, but not limited to:

- a) providing a 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);
- b) ensuring smoke does not enter a protected space. Smoke control using pressure differentials is a technique often used to protect stairwells, lifts and lobbies 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; and
- c) ensuring smoke does not exceed given tenability criteria. This approach is often used to assess areas which could become smoke logged either during means of escape or during firefighting operations, e.g. room of fire origin.

4.3.2 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.

4.3.3 Firefighting operations assistance

In extensive and multi-storey complex buildings, firefighting and rescue operations can be severely hampered by the presence of hot smoky gases. In these cases, the design criteria should reflect the specialist equipment, clothing and training available to the local fire service.

4.3.4 Property protection

Smoke control systems can be used to protect not only the contents of a building but also some aspects of the structure.

4.4 Review performance requirements

The designer should clearly outline the performance requirements of the smoke control and smoke ventilation systems. A system designed to protect property might require different input parameters and criteria to that of a system designed to protect escaping occupants or to protect firefighters.

Key criteria could include:

- a) occupant characteristics;
- b) building geometry;

- c) assessment of toxicity criteria;
- d) assessment of visibility criteria;
- e) assessment of temperature criteria (including convection and radiation);
- f) design fire sizes;
- g) impact of suppression systems;
- h) type of ventilation system; and
- i) provision of automatic fire detection.

It is for the QDR to determine the appropriate application of these different criteria.

NOTE Guidance on, for example, tenable conditions, evacuation time and structural performance is provided within the other sub-systems forming the suite of documents comprising BS 7974.

The criteria, design assumptions and performance objectives should be clearly documented within the designer's information.

4.5 Determine system types

4.5.1 General

System types for the control of smoke include:

- a) containment;
- b) removal;
- c) dilution;
- d) pressurization; and
- e) depressurization.

More information on the system types is given in [4.5.2](#) to [4.5.6](#). The correct specification of the appropriate system types to achieve the design objectives forms part of the QDR process.

4.5.2 Smoke containment

Smoke containment relies on physical barriers to limit the spread of smoky gases from one space in a building to another. Elements of passive fire protection, 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 barriers and position of the leakage paths relative to the smoke (layer).

Leakage can be substantially reduced by the incorporation of linear gap sealing systems, penetration sealing systems, smoke control door sets and their associated seals. Control of high temperature smoke can be improved with the use of intumescent seals.

For further information on quantitative measurements of smoke leakage through, e.g. door sets, see BS 476-31.1, BS EN 1634-3 and BS EN 13501-4.

4.5.3 Smoke dilution

Mixing of smoky gases with clean air to increase visibility and reduce the threat from toxic combustion products can require large volumes of clean air to achieve a measure of visibility within the range set by the QDR. With smoky fuels, such as those from many plastics materials, this dilution might 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.

NOTE Guidance on smoke dilution systems is given in CIBSE Guide E [1].

4.5.4 Smoke removal

A method of providing separation between an upper layer of smoke and a lower layer of relatively clean air 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.

NOTE Guidance on the design of smoke exhaust ventilation can be found in BRE Report 368 [2], CIBSE Guide E [1] and BS 7346 (all parts).

Methods for the removal of relatively cool smoky gases from a space in a building when smoke is no longer entering or being created in that space (i.e. smoke clearance) include natural cross-ventilation (e.g. the opening of windows) or powered smoke and heat exhaust ventilation systems.

4.5.5 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.

NOTE Guidance on the design of pressurization systems can be found in BS EN 12101-6.

The pressure difference across any small openings 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.

Pressurization systems are designed to have adequate airflow 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.

4.5.6 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 should be 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 an atrium it is possible to use the buoyancy of the smoky gases themselves to create the desired depressurization effects.

NOTE Guidance on the design of depressurization systems can be found in BRE Report 368 [2] for atria and BS EN 12101-6 for basement ventilation.

4.6 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 could also be important.

In rooms of large volume, e.g. 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 should also be taken into account by the designer as part of the QDR and design process and any assumptions documented.

NOTE Guidance on environmental influences on smoke control can be found in BRE Report 368 [2] and BS 7346-4.

4.7 Design application

4.7.1 General

The eventual purpose of smoke control calculations is typically to develop the results into a smoke control system that forms part of the overall fire engineering strategy, or demonstrate that a system is not necessary.

When the calculations are complete, the designer should ensure all project critical information is transferred to the project design/delivery team.

Where the system is being designed for a construction project that is likely to go through a tendering process, the designer should coordinate with mechanical and electrical engineers, to ensure that the design is practical to implement and the specification released for tendering truly reflects the design intent, and that the critical aspects of the system are detailed.

Smoke control systems typically comprise one or more of the following:

- a) natural smoke control systems;
- b) mechanical (fan-assisted) smoke control systems – extract or pressurization;
- c) smoke control barriers; and
- d) fire curtains.

NOTE Fire curtains have also been included here as they are similar in design but have a different function.

4.7.2 Natural smoke control systems

A natural smoke control system utilizes smoke ventilators which are designed and manufactured in accordance with BS EN 12101-2 which requires testing of key characteristics of the product including, but not limited to:

- a) life cycle testing;
- b) speed of reaction;
- c) wind and snow load testing; and
- d) heat rise testing.

NOTE 1 See BS EN 12101-2 for a full schedule of the key characteristics.

There should be a clear description of the smoke control system, including:

- 1) location and orientation of smoke exhaust ventilators, considering environmental influences;
- 2) location and orientation of inlet ventilators;
- 3) area of smoke ventilators to be provided – this should specify whether the area required is calculated as aerodynamic or geometric;
- 4) minimum number of ventilators required to avoid “plugholing”; and
- 5) advise location and capability of any interface panels that control/override the system.

NOTE 2 Non-failsafe devices require secondary power to ensure operation in the event of power failure. Secondary power might also be desirable for failsafe devices to prevent ventilators being left open in the event of power loss.

4.7.3 Mechanical (fan-assisted) smoke control systems

A mechanical smoke control system utilizes smoke ventilators which are designed and manufactured in accordance with BS EN 12101-3. When designing a mechanical extract, calculations normally result in a volume flow rate in $\text{m}^3 \text{s}^{-1}$, $\text{m}^3 \text{h}^{-1}$ or l s^{-1} , for example. A fan-assisted system can then be designed to achieve this flow using ducting or builders’ work shafts/plenums to transfer heat and