

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)

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Foreword

This Published Document (PD) is one of a series of documents published under the Fire Standards Policy Committee, and is a supporting document to BS 7974, Code of Practice on the Application of Fire Safety Engineering Principles to the Design of Buildings. Other parts in the series are:

- *Part 0: Guide to design framework and fire safety engineering procedures;*
- *Part 1: Initiation and development of fire within the enclosure of origin;*
- *Part 2: Spread of smoke and toxic gases within and 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.*

Drafting of this publication was completed in July 2001.

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

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 151 and a back cover.

Introduction

This Published Document provides a framework for developing a rational methodology for design of buildings using a fire safety engineering approach. It applies scientific and engineering principles to the protection of people, property and the environment from fire.

The Published Documents (PDs) in this series 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 BS 7974 and the associated 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.

This Published Document includes no specific analysis of some aspects of fire spread beyond the enclosure of origin other than the performance of products based upon a fire resistance furnace test. In due time, as the knowledge and understanding is improved, these areas of uncertainty will be addressed. However, in the meantime, a commentary is given on the particular issues that need to be considered and how these should be treated.

A fire safety engineering 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 can in some cases be the only viable means of achieving a satisfactory standard of fire safety in some large and complex buildings.

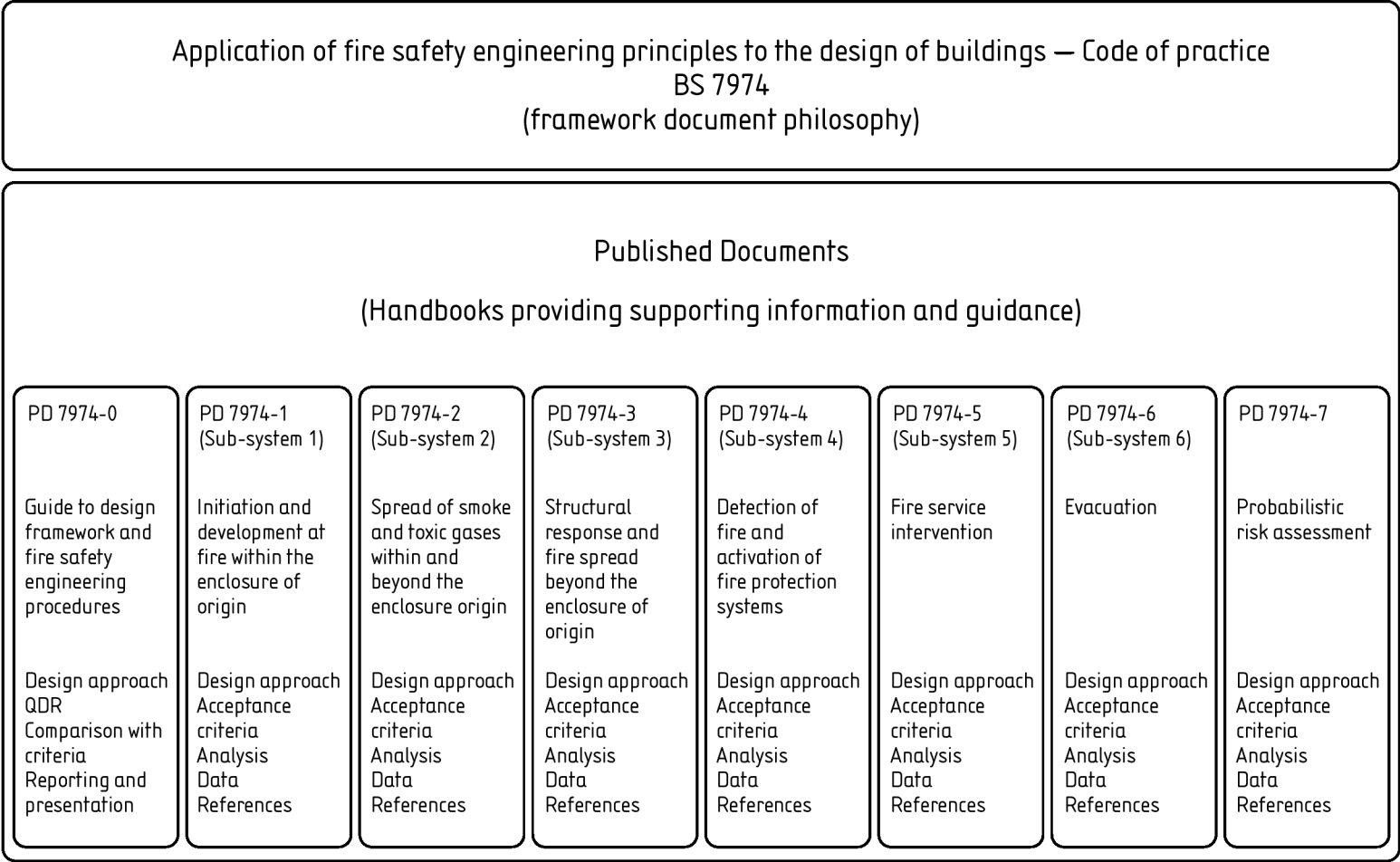


Figure 1 — Overview of the PD 7974 series of Published Documents

1 Scope

This Published Document considers the following issues:

- a) the conditions within a fire enclosure and their potential to cause fire spread by way of recognized mechanisms and routes;
- b) the thermal and mechanical responses of the enclosure boundaries and its structure to the fire conditions;
- c) the impact of these anticipated thermal and mechanical responses on adjacent enclosures and spaces;
- d) the structural responses of load-bearing elements and their effect on structural stability, load transfer and acceptable damage.

2 Normative references

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

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

3 Terms and definitions

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

3.1

enclosure

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

3.2

fire safety engineering

FSE

use of engineering principles for the achievement of fire safety

3.3

time equivalent

duration of exposure to fire test conditions specified in BS 476-20:1987 or ISO 834-1

NOTE This is equivalent (in terms of some designated effect) to exposure to the full duration of real enclosure fire conditions.

3.4

sensitivity analysis

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

3.5

structural frames

arrangement of structural materials and/or elements combined to form a building or a part thereof which has been designed to fulfil a loadbearing function

3.6

duration of steady burning

Interval between onset of flashover and commencement of decay

NOTE It is often characterized as the period over which the fire load within the enclosure is reduced from 80 % to 30 % of its initial value.

4 Symbols and abbreviated terms

A	is the cross-section area of a steel member (m^2)
A_c	is the area of concrete core (mm^2)
A_e	is the area of exposed surface (m^2)
A_f	is the floor area of enclosure (m^2)
A_h	is the area of ventilation in the horizontal plane (m^2)
A_i	is the cross section area of an insulated element (m^2)
A^*_i	is the surface area of element i , (wall, floor, roof) (m^2)
A_r	is the cross-section of steel reinforcement (mm^2)
A_{rad}	is the area of radiating surface (m^2)
A_T	is the internal solid area of the enclosure (m^2)
A_t	is the total internal area, including openings, of the enclosure (m^2)
A_v	is the area of ventilation in the vertical plane (m^2)
A_w	is the area of the openings (m^2)
$A_w\%$	is percentage of window area (%)
a	is the distance between the edge of opening and external steel column (m)
b	is the thermal inertia ($\text{J}/\text{m}^2 \cdot \text{s}^{1/2} \cdot \text{K}$)
b_e	is the exposed height of an external beam (m)
b_c	is the width of a reinforced concrete slab (mm)
b_i	is the thermal inertia of an element ($\text{W}/\text{m}^2 \cdot \text{s}^{1/2}$)
b_p	is the thermally induced movement of a partition at mid-height (mm)
b_s	is the additional bow of partition due to self weight (mm)
b_t	is the width of a timber beam (m)
C	is the specific heat capacity ($\text{J}/\text{kg} \cdot \text{K}$)
C_a	is the specific heat capacity of steel ($\text{J}/\text{kg} \cdot \text{K}$)
C_{al}	is the specific heat capacity of aluminium alloys ($\text{J}/\text{kg} \cdot \text{K}$)
C_c	is the specific heat capacity of concrete ($\text{J}/\text{kg} \cdot \text{K}$)
C_{com}	is the specific heat capacity of a fibre reinforced polymer ($\text{J}/\text{kg} \cdot \text{K}$)
C_f	is the specific heat capacity of fibre reinforcement ($\text{J}/\text{kg} \cdot \text{K}$)
C_g	is the specific heat capacity of the gases ($\text{J}/\text{kg} \cdot \text{K}$)
C_i	is the specific heat capacity of insulation layer i ($\text{J}/\text{kg} \cdot \text{K}$)
C_m	is the specific heat capacity of metal ($\text{J}/\text{kg} \cdot \text{K}$)
C_t	is the specific heat capacity of uncharred timber ($\text{J}/\text{kg} \cdot \text{K}$)
C_x	is the specific heat capacity of a composite matrix ($\text{J}/\text{kg} \cdot \text{K}$)
D	is the depth of enclosure (m)
d	is the characteristic dimension perpendicular to the direction of heat flow (m)
d_{char}	is the depth of char (mm)
d_{door}	is the thickness of a door leaf (mm)
d_i	is the thickness of insulating material i (m)
d_r	is the depth of reinforcement in a concrete slab (m)
d_s	is the thickness of the stud partition (m)
d_t	is the depth of a timber beam (mm)
d_w	is the thickness of a wall (m)
d_x	is the concrete depth normal to major axis (m)

d_y	is the concrete depth normal to minor axis (m)
E	is the Young's modulus for metal at the relevant temperature (kN/mm ²)
E_a	is the Young's modulus for steel at the relevant temperature (kN/mm ²)
E_{al}	is the Young's modulus for aluminium alloys (kN/mm ²)
$E_{d,t}$	is the design load created by the fire situation at time t
E_t	is the tangent modulus (kN/mm ²)
e_{rfc}	is the complex error function
F	is the axial load applied in fire (N)
F_d	is the design value of indirect loads created by the effect of fire
F_R	is the fire resistance time (h)
F_{wi}	is the strength of wrought iron at ambient temperature (N/mm ²)
F_{e-R}	is the configuration factor describing the spatial relationship between the emitting and receiving surfaces
F_o	is the strength of reinforcement at ambient temperature (N/mm ²)
F_s	is the strength of reinforcement at the relevant temperature (N/mm ²)
F_t	is the tensile strength of steel at the relevant temperature (N/mm ²)
F_{wo}	is the strength of wrought iron at ambient temperature (N/mm ²)
F_{wi}	is the strength of wrought iron at the relevant temperature (N/mm ²)
f	is an empirical factor (min/mm)
f_c	is the compressive strength of concrete at the relevant temperature (N/mm ²)
f_{ap}	is the stress at the proportional limit for steel at the relevant temperature (N/mm ²)
f_{au}	is the ultimate stress for steel at the relevant temperature (N/mm ²)
$f_{au,\theta}$	is the tensile strength at elevated temperatures (N/mm ²)
f_{ay}	is the yield strength of steel at temperature T_a (N/mm ²)
f_{cu}	is the cube strength of concrete (N/mm ²)
f_k	is a modification factor for ventilation
$f_{a,\text{max}}$	is the maximum stress for steel at the relevant temperature (N/mm ²)
f_o	is the concrete strength at ambient (298 K) temperature (N/mm ²)
f_s	is the steel stress (N/mm ²)
f_y	is the yield strength of steel (N/mm ²)
$f_{0.2}$	is the 0.2 % proof stress of steel (N/mm ²)
G_k	is the characteristic value of the permanent dead load
H	is the height of the enclosure (m)
ΔH	is the heat of combustion of a fire load material (kJ/kg)
H_{door}	is the key linear dimension of the door leaf (mm)
H_p	is the heated perimeter of a section (m)
H_{roof}	is the difference in height between the plane of the horizontal opening and the neutral axis of the gas in the vertical opening (m)
H_w	is the opening height (m)
H_{wall}	is the height of wall (mm)
h_p	is the partition height (mm)
I	is the second moment of area (mm ⁴)
$K_{0,1,2}$	are constants relating to the fire protection material
K	is the thermal diffusivity (m ² /s)

K_b	is the buckling factor
K_c	is the thermal diffusivity of concrete (m^2/s)
k	is the thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)
k_a	is the thermal conductivity of steel ($\text{W}/\text{m}\cdot\text{K}$)
k_{al}	is the thermal conductivity of aluminium alloys ($\text{W}/\text{m}\cdot\text{K}$)
k_b	is the factor describing the thermal properties of the enclosure
$k_{bolt,\theta}$	is the reduction factor for bolts (tension and shear)
k_c	is the thermal conductivity of concrete ($\text{W}/\text{m}\cdot\text{K}$)
k_{comp}	is the thermal conductivity of a composite ($\text{W}/\text{m}\cdot\text{K}$)
k_f	is the thermal conductivity of fibre reinforcement ($\text{W}/\text{m}\cdot\text{K}$)
k_i	is the thermal conductivity of an insulation layer i ($\text{W}/\text{m}\cdot\text{K}$)
k_t	is the thermal conductivity of uncharred timber ($\text{W}/\text{m}\cdot\text{K}$)
k_x	is the thermal conductivity of a composite matrix ($\text{W}/\text{m}\cdot\text{K}$)
l	is the distance along a flame (m)
L	is the total fire load in enclosure either in wood equivalent (kg) or heat content (MJ)
ΔL	is the expansion of a door leaf (mm)
L_0	is the linear dimension at ambient temperature (mm)
L_R	is the load ratio
L_T	is the linear dimension at temperature T (mm)
ΔL_T	is the temperature induced expansion (mm)
M	is the mass outflow rate of hot gases (kg/s)
M_b	is the moment resistance to lateral torsional buckling ($\text{N}\cdot\text{m}$)
M_c	is the moment capacity of section about appropriate axis of bending ($\text{N}\cdot\text{m}$)
M_f	is the applied moment in fire ($\text{N}\cdot\text{m}$)
M_{fx}	is the moment about major axis in fire ($\text{N}\cdot\text{m}$)
M_{fy}	is the moment about minor axis in fire ($\text{N}\cdot\text{m}$)
$M_{opening}$	is the mass flow rate in plume, at height Z_w (kg/s)
M_{px}	is the plastic moment capacity of reinforcement about major axis ($\text{N}\cdot\text{m}$)
M_{py}	is the plastic moment capacity of reinforcement about minor axis ($\text{N}\cdot\text{m}$)
M_{stud}	is the moment in the stud due to thermal induced eccentricity ($\text{N}\cdot\text{m}$)
m	is the equivalent uniform moment factor
m_s	is the stud spacing (mm)
$N_{pl,fi,Rd}$	is the compressive resistance in fire
$N_{pl,Rd}$	is the compressive resistance in normal design
n	is the weight of the partition per metre height (kN)
n_s	is the ratio between the gas and surface temperatures of a concrete member
n_x	is the ratio between surface temperature and the temperature at depth x in a concrete member
n_y	is the ratio between surface temperature and the temperature at depth y in a concrete member
O	is the opening factor ($\text{m}^{1/2}$)
P	is the % of moisture (by mass)
P_b	is the buckling load (kN)
p_c	is the compressive strength of concrete (N/mm^2)
p_y	is the characteristic design stress for steel (N/mm^2)

p_{yr}	is the characteristic yield strength for steel reinforcement (N/mm ²)
Q	is total heat release
Q_c	is the rate of heat loss by convection (kW)
Q_g	is the rate of accumulation of heat in the hot gases (kW)
Q_k	is the characteristic value of the imposed load
$Q_{k,i}$	are the characteristic values of the other variable live loads, e.g. wind
$Q_{k,1}$	is the characteristic value of the dominant load
Q_r	is the rate of heat loss by radiation through the openings (kW)
Q_{total}	is the total rate of heat release in the enclosure (kW)
Q_w	is the rate of heat flow to enclosing construction (kW)
q	is the fire load density per unit area of enclosure surface or floor area (MJ/m ²)
q_c	is the convective heat flux (kW/m ²)
q_{cond}	is the conductive heat flow (kW)
q_{conv}	is the convective heat flow (kW)
q_{net}	is the net incident heat flux (kW/m ²)
q_r	is the radiative heat flux (kW/m ²)
q_{rad}	is the radiative heat flow (kW)
q_{rec}	is the radiative heat flux received by the surface outside the fire enclosure (kW/m ²)
q_{total}	is the total heat flux (kW/m ²)
R	is the burning rate (kg/s)
$R_{d,t}$	is the design resistance of the member or structure to the fire created situation at time t
S_i	is the thickness of layer i (m)
S_{limit}	is the limiting depth of boundary (m)
T	is temperature (°C or K)
ΔT	is a temperature interval (°C or K)
ΔT_{stud}	is the temperature difference between the hot and cold faces of a stud partition (°C)
T_a	is the steel temperature (K)
T_{al}	is the aluminium alloy temperature (K)
T_c	is the concrete temperature (K)
T_{door}	is the temperature of the door leaf (K)
T_{exp}	is the exposed wall surface temperature (°C)
T_g	is the gas temperature in the enclosure or furnace (K)
T_g^{max}	is the maximum gas temperature in fire enclosure (K)
T_m	is the metal temperature (K)
T_o	is ambient temperature (293 K)
$T_{opening}$	is the gas temperature in the plane of the opening (K)
$T_{surface}$	is the material surface temperature (K)
ΔT_{stud}	is the temperature difference between the hot and cold faces of a stud partition (°C)
T_t	is the temperature of uncharred timber (K)
T_{unexp}	is the unexposed wall surface temperature (°C)
T_{wi}	is the wrought iron temperature (°C)
$T_{x,t}$	is the temperature at location x and time t (K)
T_z	is the temperature at any point along the flame (K)
t	is time (s, min or h)

Δt	is a time interval (s)
t_{char}	is the charring rate (mm/min)
$t_{\text{char}}^{\text{max}}$	is the maximum charring rate (mm/min)
t_{d}	is the dwell time (min)
t_{e}	is the time equivalent (min)
t_{ed}	is the design time for an equivalent duration of heating in the standard furnace test (min)
t_{fr}	is the fire resistance time (min)
t_{s}	is scaled time (h)
t^*	is the modified time (h) ($t^* = \Gamma.t$)
t_{max}^*	is the time to reach maximum temperature (h)
u	is the wind speed (m/s) (generally taken as 6 m/s)
V	is the steel volume (m ³)
V_{f}	is the fibre volume fraction of a composite
V_{i}	is the volume per unit length of an insulated element (m ³)
V_{x}	is the matrix volume fraction of a composite
W	is the width of enclosure (m)
w	is the width of the opening (m)
w_{f}	is the width of the flame front (m)
w_{v}	is a ventilation factor (dimensionless)
X	is the flame length along axis (m)
x	is the horizontal projection of the flame (m)
x_{a}	is the depth of the neutral axis (m)
x_{s}	is the distance from exposed surface (m)
Z	is the flame height above opening (m)
Z_{y}	is the elastic modulus about the minor axis (cm ⁴)
Z_{w}	is the height above the top of the opening (m)
z	is the vertical projection of the flame above the window (m)
z_{c}	is the lever arm between the centroid of the effective stress block and the neutral axis
α	is the coefficient of thermal expansion
α_{c}	is the coefficient of heat transfer by convection (W/m ² ·K)
Γ	is the compartment time factor
γ_1	is the safety factor reflecting the consequences of failure by the enclosure
γ_2	is the safety factor reflecting the risk of a fully developed fire taking place in the enclosure
γ_3	is the safety factor reflecting the benefits of installing an automatic sprinkler system to BS 5306-2 within enclosure
γ_{c}	is the material strength partial safety factor for concrete (1.3)
γ_{conv}	is a coefficient for heat transfer by convection
γ_{G}	is the partial safety factor for permanent loads to be assigned a value of 1.0
γ_{rad}	is a coefficient for heat transfer by radiation
γ_{s}	is the material strength partial safety factor for steel (1.0)
Δ_{bow}	is the lateral deflection of a wall (mm)
Δ_{dis}	is the displacement (mm)
Δ_{head}	is the deflection of head of wall away from the heat source (mm)
ε	is strain
ε_{a}	is strain at the relevant temperature

$\varepsilon_{a,max}$	is the strain at the maximum stress corresponding to 2.0 % strain
ε_{ap}	is the strain at the proportional limit at the relevant temperature
ε_{au}	is the strain at the ultimate stress at the relevant temperature
ε_c	is strain corresponding to 0.2 % proof stress at the relevant temperature
ε_f	is the emissivity of the fire
ε_{fl}	is the emissivity of the flames
ε_g	is the emissivity of the fire gases
ε_{rec}	is the emissivity of the receiving surface
ε_{res}	is the resultant emissivity
ε_s	is the emissivity at the surface of a material
$\varepsilon_{surface}$	is the emissivity of the surface
η	is the load ratio of a concrete filled hollow section
$\eta_{fi,t}$	is the strength ratio at temperature ($\gamma_{1,2,3}$ are safety factors)
θ	is temperature (°C or K)
λ	is the thickness of the flame (m)
ϕ	is the configuration factor
ρ	is density (kg/m ³)
ρ_a	is the density of steel (kg/m ³)
ρ_{al}	is the density of aluminium alloys (kg/m ³)
ρ_c	is the density of concrete (kg/m ³)
ρ_f	is the density of fibre reinforcement (kg/m ³)
ρ_i	is the density of the insulation layer i (kg/m ³)
ρ_m	is the density of metal (kg/m ³)
ρ_t	is the density of timber (kg/m ³)
ρ_x	is the density of a composite matrix (kg/m ³)
ρ_w	is the density of water (kg/m ³)
σ	is the Stefan Boltzman constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$)
σ_a	is the applied stress at the relevant temperature (N/mm ²)
ψ	is $L/(A_w A_T)^{0.5}$ (kg/m ²)
$\psi_{i,j}$	are partial safety factors for variable loads
$\psi_{1,1}$	is a partial safety factor for the primary variable load
$\psi_{2,i}$	are the partial safety factors for the secondary variable loads

5 Design approach

5.1 Design principles

5.1.1 *Experience and qualifications*

The complexity of the interactions between people, buildings and fire is such that no single set of calculation procedures can be applied to all types of buildings in all circumstances. Therefore, FSE requires a greater degree of care and responsibility by the designer than does the application of prescriptive codes. It is therefore essential that the application of FSE be entrusted to suitably qualified and experienced personnel.

5.1.2 *Methodology for design — General*

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

The quantitative analysis necessary as part of the design process is divided into a number of separate parts or sub-systems. Each sub-system may be used in isolation when analysing a particular aspect of design or they may be used in combination as part of an overall fire evaluation of a building. A representation of the concept is shown in Figure 2. Some of the potential interactions between sub-systems are illustrated. The parameters are often both inputs into one sub-system and outputs from another.

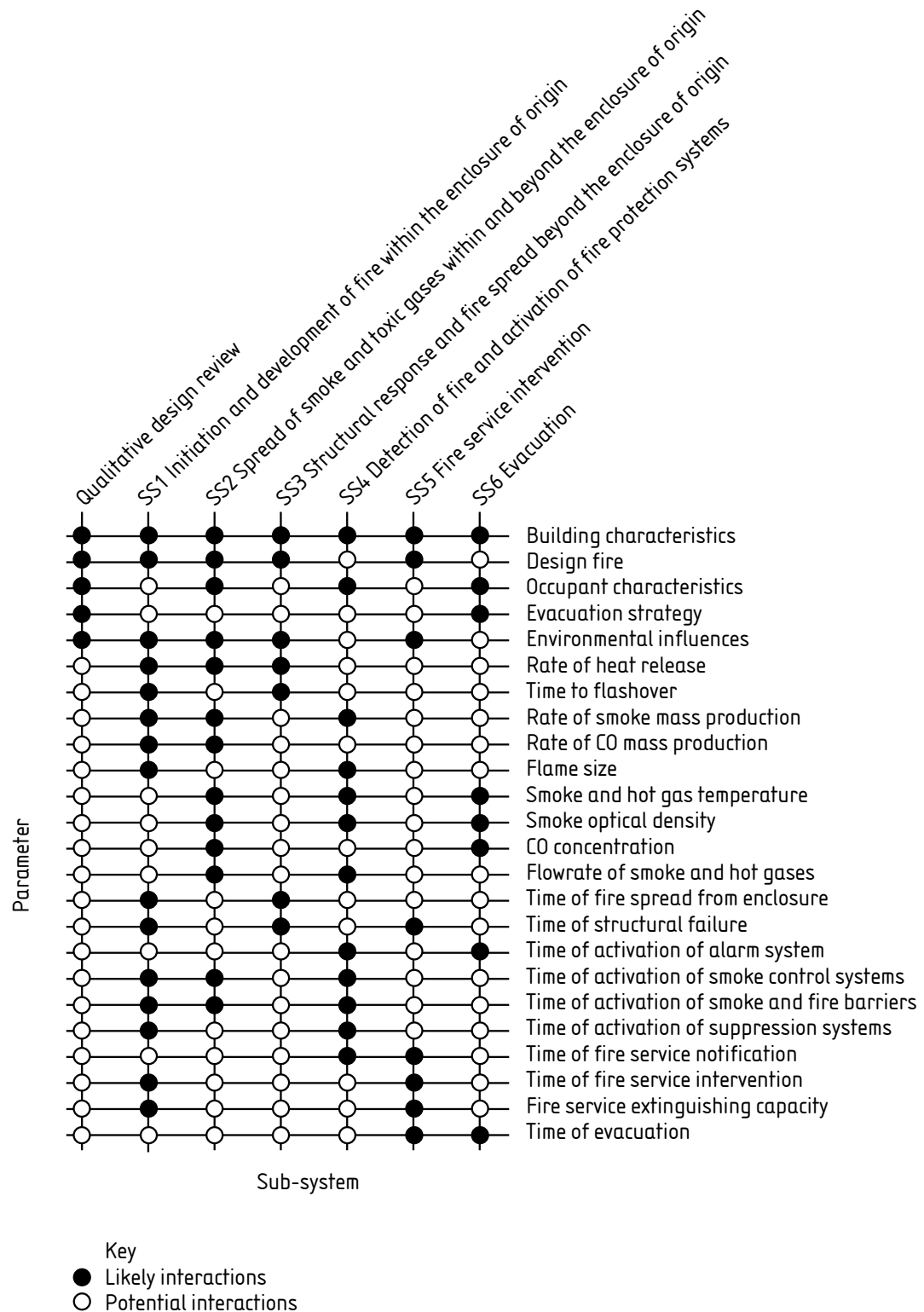


Figure 2 — Methodology for design of all sub-systems in the PD 7974 series

5.1.3 Methodology for design with respect to sub-system 3

The methodology for design of sub-system 3 is outlined in Figure 3.

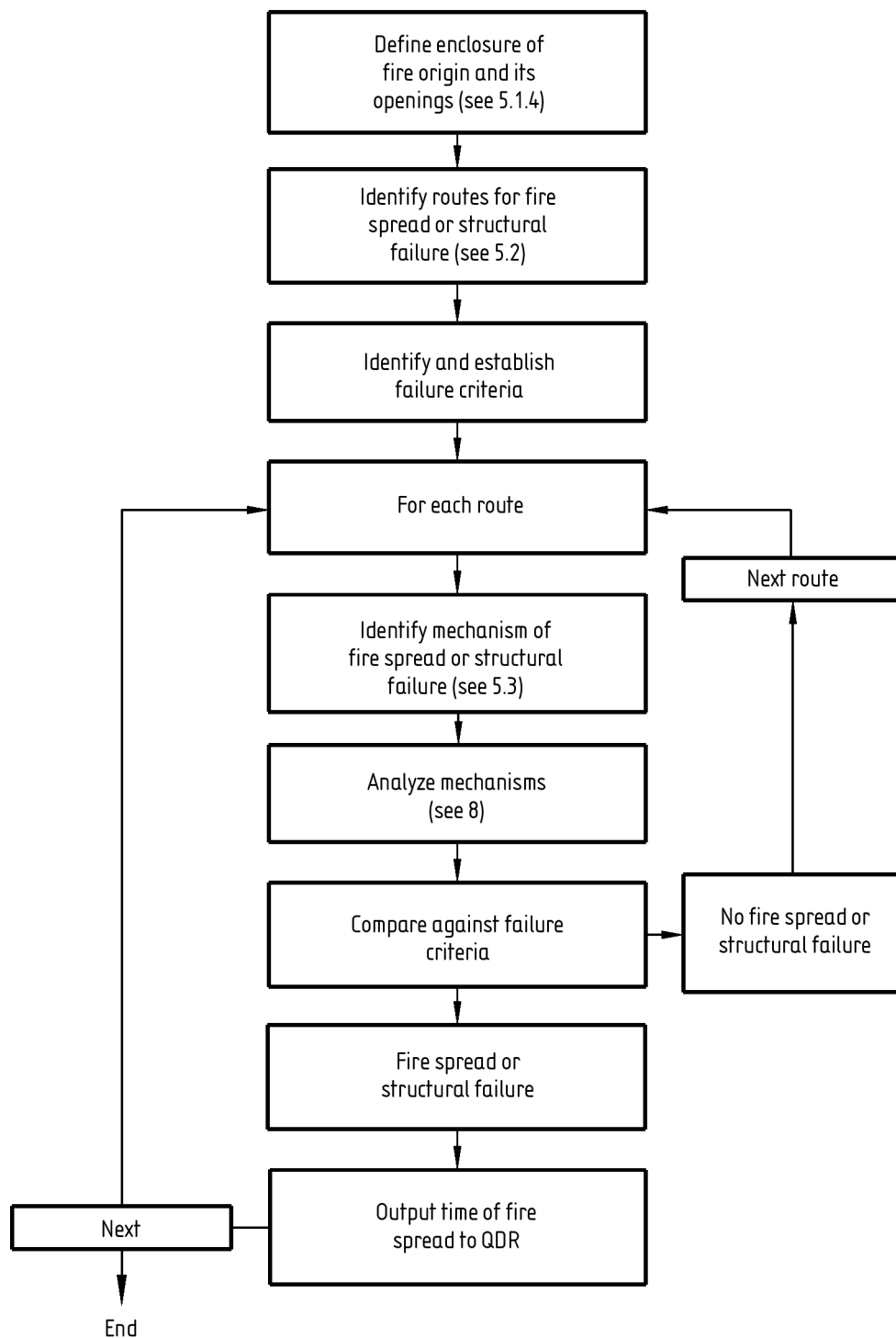


Figure 3 — Methodology for design of sub-system 3

5.1.4 Description of the fire enclosure

All solid boundaries in a building will inhibit the spread of fire to some extent. Certain boundaries in a building are purpose designed to prevent fire spread and are generally tested in a standard furnace to assure their fire-resisting performance. The fire safety strategy [established in the Qualitative Design Review (QDR); see PD 7974-0] will designate those boundaries required to resist fire spread. Nonetheless, any surface bounding a space in which a fire can occur will enclose the fire to some extent. This is particularly important in terms of the rate of growth of the fire and the development of temperatures within the space. The ongoing capacity of these initial enclosing surfaces to remain imperforate to the spread of fire will be a function of their construction and the fire condition, which can be changing. Accordingly, the nature of the fire enclosure should be viewed as being time-dependent and will need ongoing analysis as described in this sub-system.

When characterizing the enclosure of fire origin, the following guidance is offered.

- In the context of predicting pre-flashover fire conditions, the horizontal and vertical surfaces immediately surrounding the fire should be considered as the enclosure.
- The enclosure can also contain openings (see 5.1.5) which, although immediately and directly open to the passage of fire and heat, may be characterized as part of the enclosing boundaries.
- After flashover has occurred, solid boundaries may be assumed to remain imperforate to fire for that duration when no openings are created in the surfaces due to their mechanical response on exposure to fire. Guidance on the prediction of fire created openings is given in Clause 8 and Clause 13.
- As the definition of the enclosing surfaces is changed by the creation of openings, the fire conditions might need to be re-examined and fire spread routes re-evaluated.
- Design may be simplified by assuming the enclosure is bounded only by those surfaces that have a determinate fire resistance rating. Enclosures viewed in this manner are often described as fire compartments. Intermediate boundaries without determinate fire resistance ratings are ignored. The compartment may be evaluated to ascertain the fire conditions and the consequent potential for fire spread. The possibility of more severe conditions developing locally within the compartment need not be considered. For example, whilst it may be that a fire occurring in a small enclosure within a large compartment can be more severe than the fire in the entirety of the larger compartment, the definition of the larger space as a single compartment during the QDR will have taken this into consideration.

5.1.5 Characterization of openings (doors, windows, vents, etc.) under non-fire conditions

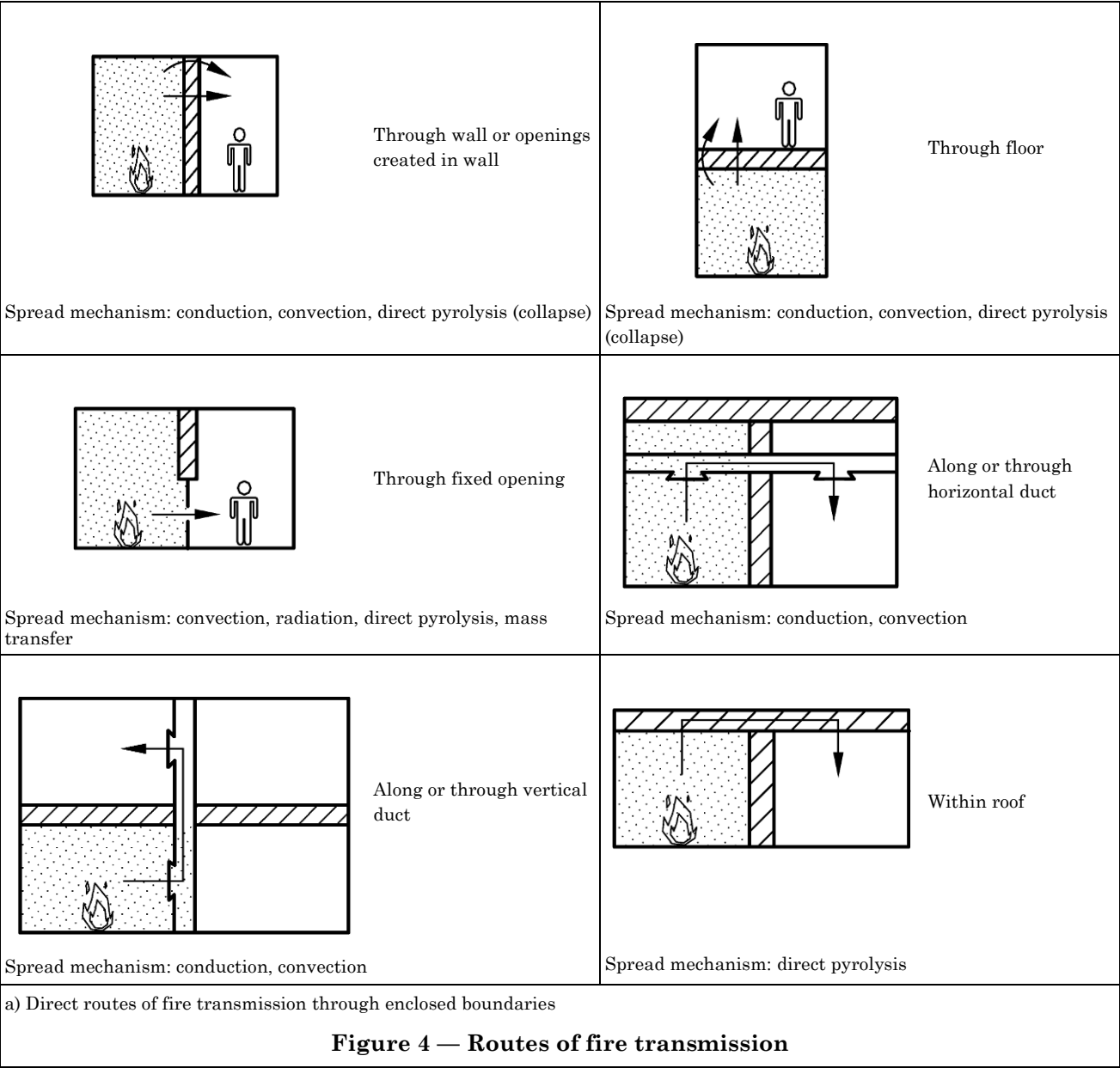
The fire conditions within an enclosure depend on the size, shape and extent of openings, which permit airflow to the fire, and ventilation of heat. Where a combination of fixed opening conditions is possible for the fire enclosure (e.g. some doors open, some doors closed), options which are most conducive to fire spread should be considered, i.e. a worst case scenario. The assumption that all openings are initially open might not necessarily be the worst case. The following guidance is offered.

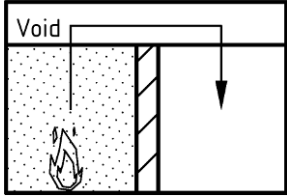
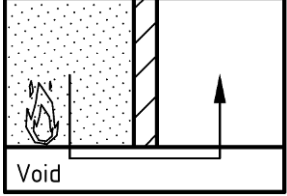
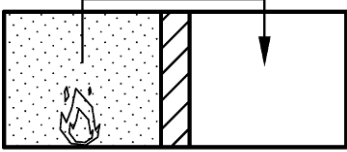
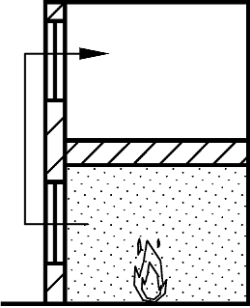
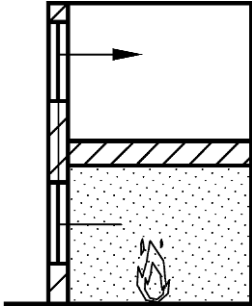
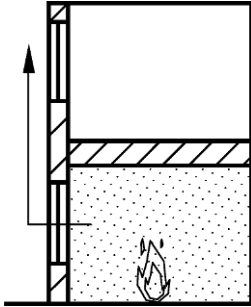
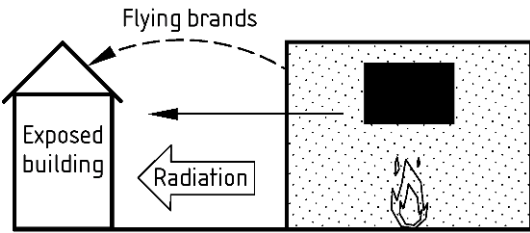
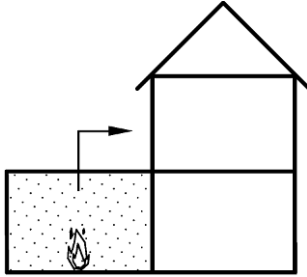
- Doors should be assumed open if the enclosure has no other openings.
- Doors should be assumed closed if the enclosure has other openings.
- All enclosure surfaces (including glazed openings) may be assumed to be imperforate for the duration of the fire provided analysis has shown that the conditions have not created openings; see Clause 8 and Clause 13.
- Large numbers of combinations of opening condition may be simulated using Monte Carlo type modelling techniques, allowing the designer to evaluate the robustness of the design solution.

5.2 Routes for fire spread

Once the enclosure of fire origin has been characterized, the designer should identify all of the possible routes of fire transmission through the boundary surfaces. Figure 4a) illustrates some of the more common direct routes for potential fire spread. In many instances, designers also need to consider the potential for fire spread between two adjoining enclosures via independent spaces as illustrated in Figure 4b). These routes of fire spread represent a combination of direct spread routes and should be examined as a series of direct spread mechanisms.

Ideally, all of the potential routes for fire spread from the enclosure should be investigated and the minimum time for fire spread determined. However, design effort may be reduced in situations where expert judgement can identify those routes susceptible to the most rapid fire spread. The minimum fire spread time is necessary for the QDR. It should be remembered that the determination as to whether or not fire spread takes place will be influenced by conditions both within the fire enclosure and within the adjacent enclosures/spaces.



 Above ceiling Spread route: 1. Enclosure to ceiling void 2. Void to adjacent enclosure	 Below floor Spread route: 1. Enclosure to floor void 2. Void to adjacent enclosure
 Over external roof Spread route: 1. Enclosure to roof 2. Roof to adjacent enclosure	 Via windows Spread route: 1. Enclosure to outside 2. Outside to adjacent enclosure
 Within facade or building envelope Spread route: 1. Enclosure to facade 2. Facade to adjacent enclosure	 Surface of facade Spread route: 1. Enclosure to facade 2. Facade to adjacent enclosure
 Spread route: radiation/mass transfer/direct pyrolysis	 Via external route Spread route: 1. Enclosure to roof outside 2. Roof flames through external envelope, e.g. window
b) Combined routes of fire transmission from enclosure potentially leading to fire spread Figure 4 — Routes of fire transmission (continued)	

5.3 Mechanisms for fire spread

5.3.1 Introduction

Assuming that fire starts within an enclosure, fire could potentially spread to adjacent enclosures or spaces as the individual or combined result of heat transmitted by:

- a) conduction;
- b) convection;
- c) radiation;
- d) mass transfer;
- e) direct pyrolysis.

5.3.2 Conduction

The solid boundaries of an enclosure will have one surface exposed to fire conditions whilst the other non-exposed surface will face into the adjacent enclosure/space. An excessive flow of heat from the exposed to the non-exposed surfaces of the boundary elements can lead to transmission of fire to adjacent spaces. Traditionally, fire spread by this mechanism has been referred to as insulation failure of the enclosure.

Heat can be transmitted from the enclosure by way of direct conduction to the non-exposed side of boundary elements or by indirect conduction through building components that are continuous to outside the enclosure, e.g. pipes, ducts, beams, columns.

Whether the heat conducted to the non-exposed surface causes transmission of fire will depend on the effect such heat may have on adjacent spaces. The heat conducted to the non-exposed surface from the fire enclosure may precipitate fire spread as follows:

- ignition of the non-exposed surface;
- conduction of heat from non-exposed surface to combustibles with which it has direct contact;
- convection of heat from non-exposed surface to adjacent combustibles;
- radiation of heat from non-exposed surface to adjacent combustibles.

It is possible to inhibit this fire spread mechanism through prevention of the above scenarios. However, the conductive heating of the non-exposed surface might need to be considered separately in terms of its potential effect on building occupants.

5.3.3 Convection

The excessive flow of hot gases or flames through openings in the enclosure can cause ignition of combustible items in adjacent spaces. The flow of hot gases from the enclosure can be by way of the fixed openings from the enclosure (as defined in 5.1.5) or openings that have occurred as a result of fire. Traditionally, fire spread by this mechanism is termed integrity failure of the enclosure. In addition, collapse of the boundary element, e.g. due to its failure to remain sufficiently load-bearing under fire conditions, can also permit transmission of fire through excessive convection.

Heat flow through openings is one of the most difficult parameters to quantify, particularly in the stage between initial integrity failure and total collapse.

5.3.4 Radiation

The transmission of heat from openings in the enclosure may cause ignition of adjacent combustible items. Heat can be radiated from fixed openings (e.g. doors and windows) or openings which have occurred as a result of fire.

5.3.5 Mass transfer

It is possible that burning fuel items within the enclosure can be transferred from the enclosure through fixed or fire created openings. Examples include the projection of flying brands and the flowing of liquid pool fires under doors having no bund protection.

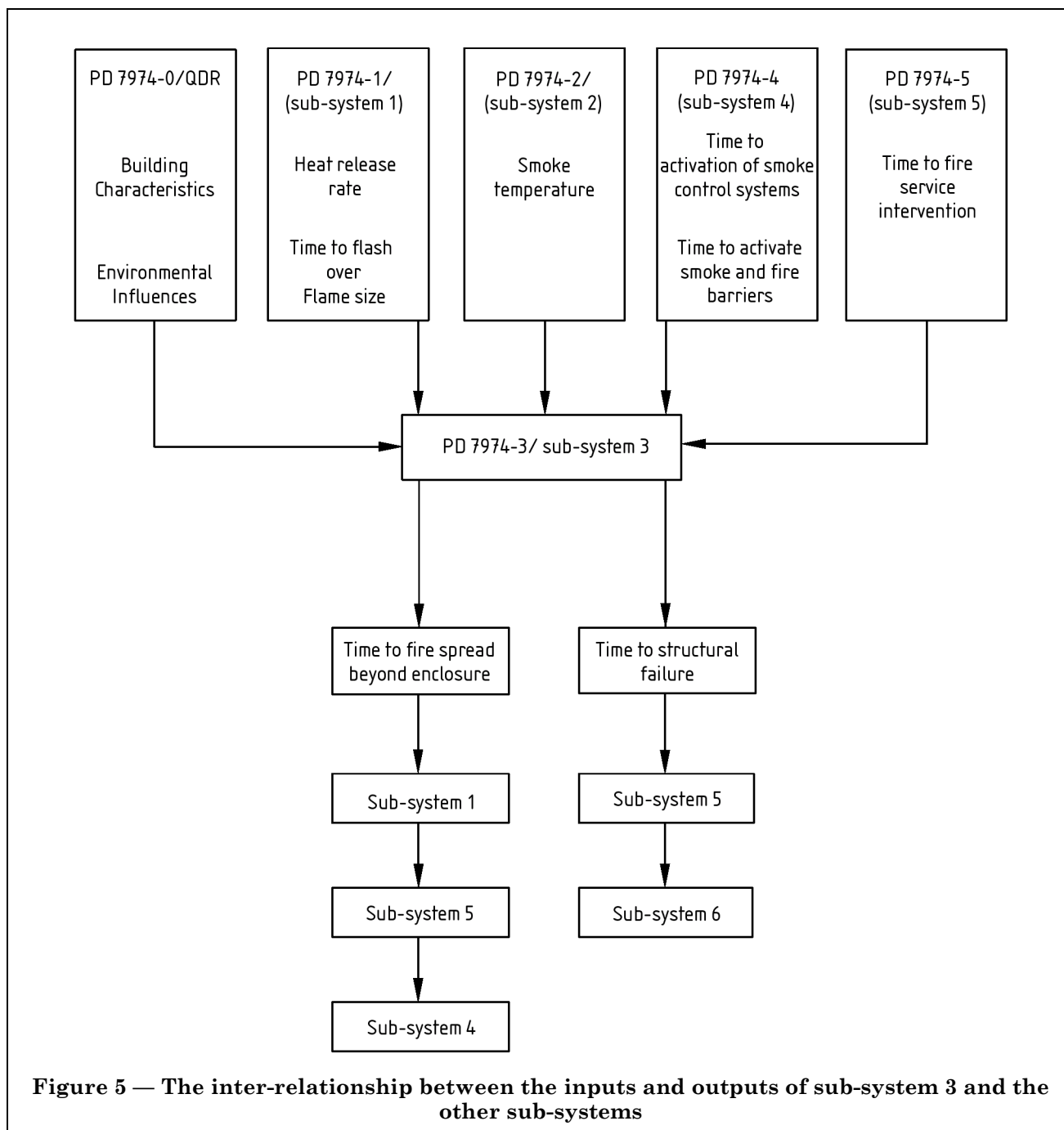
5.3.6 *Direct pyrolysis and reaction to fire*

Where boundary elements are combustible and continuous outside the enclosure, it is possible that pyrolysis can extend beyond the enclosure. Examples include lateral fire spread within the thickness of combustible walls and roofs. Successful fire stopping of such pyrolysis routes will be influenced by the reaction to fire characteristics of the materials present as well as the mechanical stability of the overall system. For example, continuous members extending beyond the enclosure of fire origin can permit fire spread by pyrolysis via some continuous combustible component. Fire stopping may be impaired by local collapse or deformation of the non-combustible part of the system. The collapse of enclosure boundaries can also permit fire to spread by direct pyrolysis.

5.4 Factors influencing fire spread

The likelihood of fire spreading beyond its enclosure can be influenced by the following factors.

- The ability of the boundaries of the enclosure to resist the passage of fire depends on their fire resistance. For example, boundaries designed to be fire-resisting (in accordance with BS 476-20, BS 476-21 and BS 476-22) can successfully resist the passage of a fully developed fire for a known minimum period.
- The anticipated fire severity in the enclosure that can be determined by the amount of fire load and ventilation present.
- Measures to reduce the severity of a fire will similarly reduce its capacity to penetrate enclosure boundaries. Fire severity can be reduced using direct measures of fire control such as installation of an automatic sprinkler system. Control of fire severity can also be exercised indirectly through design measures such as limiting the ventilation available to the fire or limiting the amount of combustibles available to fuel it.
- The size of the enclosure can also influence the potential severity of any fire that does occur. Fires in large enclosures with high ceilings, e.g. atria or single storey commercial premises, are more likely to remain fuel controlled and less likely to reach flashover.
- Access to open vertical shafts such as stairways, lift shafts or service ducts can increase fire severity through introduction of ventilation and through draughts. Vertical routes also have the potential to permit fire spread in the absence of appropriate fire dampers.
- The presence of concealed spaces (e.g. above false ceilings, within hollow construction, under floors) can increase the potential for fire to spread undetected.
- The air pressure conditions within the enclosure and more particularly pressure differentials between enclosures will influence the potential for fire spread. Fire severity can be reduced by the release of heat through ventilation from the enclosure. Further, fire and hot gases are less likely to spread into adjacent enclosures if they are maintained at a higher pressure than the fire enclosure. This principle of positive pressurization is used to protect stair shafts.
- The extent of openings within the enclosure boundaries will influence the potential for fire spread. Casual loss of air-tightness through poor workmanship in construction and unstopped joints and service penetrations can provide easy routes for fire spread.
- The deformation of structural elements can open gaps in the enclosures' boundaries in a gradual or sudden manner, e.g. through application of load to non-loadbearing assemblies.
- The potential for fire spread through voids behind curtain walling systems will be influenced by the ongoing performance of the system under conditions of fire exposure. Some systems incorporating, for example, glazing, aluminium and steel faced composite panels, can distort or otherwise react to fire exposure in a manner that allows fire to by-pass the fire-stopping.



6 Inputs

6.1 Introduction

The relationship between the inputs to sub-system 3 and the other sub-systems is shown in Figure 5.

6.2 Building characteristics

6.2.1 General

The definition of the enclosures within the building, the characterization of their key properties and the quantification of key parameters will permit determination of the effects of a fire on the integrity of the enclosure and its structural form.

6.2.2 Enclosure layouts and geometries

The layout and geometry of the enclosure will influence the thermal conditions to be expected in the event of a fire and the mechanical response of the enclosure to such conditions.

Where there is more than one opening into an enclosure, the total area for the enclosure, A_w , may be considered as the cumulative total of individual ventilation areas, i.e.

$$A_w = A_{w1} + A_{w2} + \dots A_{wi} \quad (1)$$

The characteristic width of openings for the enclosure, w , can be calculated from the cumulative total of individual opening widths as follows:

$$w = w_1 + w_2 + \dots w_i \quad (2)$$

Where an enclosure contains multiple openings, their characteristic height, h_w , can be taken to be the weighted mean height, i.e.

$$h_w = \frac{h_{w1}A_{w1} + h_{w2}A_{w2} + \dots h_{wi}A_{wi}}{A_w} \quad (3)$$

The identification of ventilation openings and potential routes for fire spread should take into consideration the issues discussed in Clause 5.

Where enclosures contain openings in the horizontal plane, the flow patterns of fire gases become more complicated. Pettersson *et al.* [1] provides guidance on considering horizontal openings where the extent of horizontal openings satisfies the relationship:

$$\frac{A_h \sqrt{h_{\text{roof}}}}{A_w \sqrt{h_w}} \leq 1.76 \quad (4)$$

If the relationship of equation (4) is not satisfied, the nomogram cannot be used and the flow through the horizontal openings is overly significant to be treated using simplistic models. In such cases, PD 7974-2 gives guidance on the flow of hot gases via horizontal vents.

The area of equivalent ventilation in such circumstances should be determined by use of a modification factor, f_k , as follows:

$$A_w = f_k A_h \quad (5)$$

The modification factor, f_k , is a function of the geometry of the enclosure and is described in a nomogram in Figure 6.

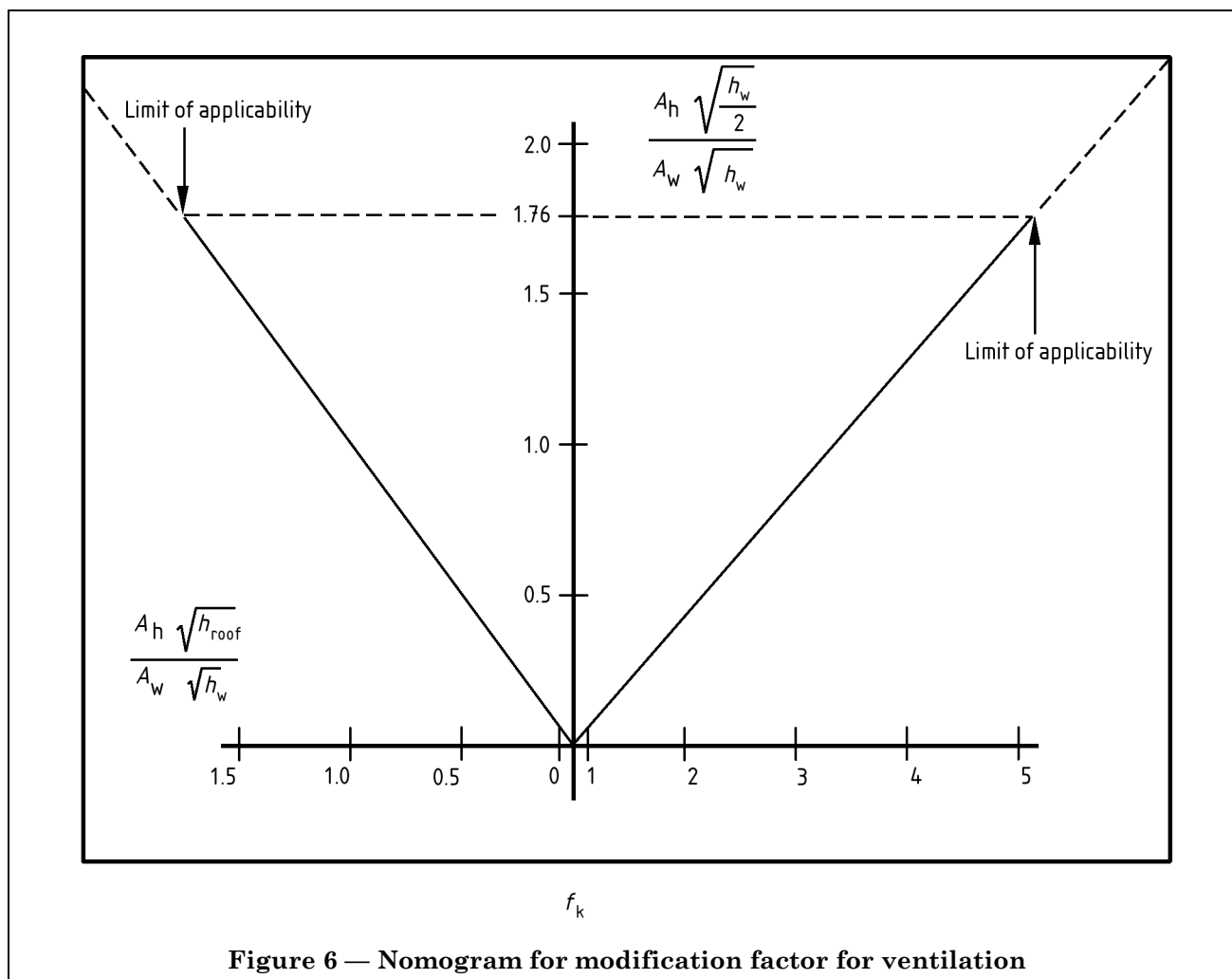


Figure 6 — Nomogram for modification factor for ventilation

6.2.3 Construction details

It is important for the designer to understand the constructional form of the enclosure and to identify any load paths that might be present. The details of the structural members within the enclosure might be required including:

- identification of load-carrying members and tracing of load paths to ground;
- quantification of the dimensions and structural properties of elements of structure;
- identification of support conditions.

The thermal characteristics of the surfaces bounding the enclosure should be understood in the context of evaluating the expected fire conditions. The key parameters include thermal conductivity, k , density, ρ , and specific heat capacity, C .

Annex A gives some data illustrating the order of these properties for some typical construction materials. These properties will change at elevated temperatures and should be used with caution. Ideally, high temperature properties should be used throughout the temperature range. In the absence of this, the properties at 500 °C may provide a reasonable approximation. However, in the limited context of predicting enclosure conditions, the ambient temperature data in Annex A may be used, but these could lead to underestimates of up to 25 %.

Other potentially significant parameters in relation to the high temperature response of materials include moisture content, water of hydration, phase changes and chemical changes that can result in exothermic or endothermic reactions.

The thermal properties of the enclosure linings may be usefully combined as a set of parameters that are widely used in analysis.

The thermal diffusivity, K , can be defined as:

$$K = \frac{k}{\rho C} \quad (6)$$

and provides a measure of the surface temperature expected on the enclosure boundary.

The thermal inertia, b , can be defined as:

$$b = \sqrt{k\rho C} \quad (7)$$

and provides a measure of the heat absorbed into the boundary element.

Information on the thermal properties for some materials is given in Table A.1 and Table A.2. It is noted that the thermal diffusivity can differ by at least two orders of magnitude and will have a significant effect on the compartment temperatures and heat loss through the linings.

The thermal inertia, b , for the enclosure should be averaged spacially to consider the differing thermal inertia of walls, floors, ceilings, etc. as follows:

$$b = \frac{A_1 * b_1 + A_2 * b_2 + \dots A_i * b_i}{A_1 * + A_2 * + \dots A_i * } \quad (8)$$

If enclosure surfaces are constituted of layers of different materials, e.g. gypsum plasterboard over concrete blocks, the overall thermal inertia for the boundary should be calculated by:

$$b = \frac{\sqrt{k_1 S_1 C_1 + k_2 S_2 C_2 + \dots k_i S_i C_i}}{\sqrt{\frac{S_1}{\rho_1} + \frac{S_2}{\rho_2} + \dots \frac{S_i}{\rho_i}}} \quad (9)$$

Whilst it is clear that the thermal inertia of an enclosure boundary surface should consider the effect of its constituent layers, there is a depth beyond which underlying layers will not impact on the thermal conditions within the enclosure. For example, a 200 mm thick concrete block wall rendered with 25 mm gypsum plaster on the fire exposed surface would generate different fire severity conditions than those if the gypsum plaster were applied on the unexposed face. Equation (9) takes no account of this effect and a simple rule of thumb may be that boundary layers need only be considered up to a limiting depth:

$$S_{\text{limit}} = 0.35 \sqrt{Kt} \quad (10)$$

where:

t is the time duration of heating(s).

Assuming for example that the fire conditions within the enclosure will be of interest for a one hour period and that the enclosure is bounded by a multi-layered lining material having diffusivities of the order of $5 \times 10^{-7} \text{ m}^2/\text{s}$ then, generally, only the layers within 15 mm of the exposed surface should be considered when calculating the thermal inertia, b .

6.2.4 Structural loads acting

The designer might need to identify the nature and magnitude of the loads as actions imposed on the structural members within the enclosure. These loads may include self-weight, permanent dead loads and various live loads. Guidance on the combination of loads is given in 11.1.

6.2.5 Fire load

The quantity of combustible material both within the enclosure and forming part of the building fabric will influence the fire conditions. PD 7974-1 establishes quantity of fire load present and includes tables describing typical fire load densities for different occupancies and calorific values of building materials.

6.2.6 Characterization of adjacent enclosures, spaces and buildings

In order to evaluate whether fire spreads from the enclosure of origin to some other space, it is necessary to consider whether the products of the fire as they escape the fire enclosure, e.g. via openings, cause ignition of combustible items in the remote space. The designer may need to characterize the layout and geometry of the adjacent enclosure(s), the construction details and the ignitability of the fire load present (if any). Should the analysis described in this part of PD 7974 indicate that ignition of items occurs in an enclosure adjacent to the enclosure of fire origin, subsequent determination of fire growth and development in the adjacent enclosure should be undertaken in accordance with PD 7974-1.

6.3 Environmental influences

The climatic conditions external to the enclosure of fire origin, e.g. wind, may influence the nature and magnitude of flames issuing from openings. The effect is discussed in 9.4.4. The designer might need to be aware of the prevailing wind direction and its design velocity (in metres per second). Similarly, snow loads or seismic loads might need to be considered in determining the mechanical response of elements of structure.

6.4 Rate of heat release

The rate of heat release expected at all times during the combustion phase of the fire is a necessary design input in several contexts. PD 7974-1 provides guidance on determining the heat release rate.

6.5 Enclosure temperature

PD 7974-1 describes models for predicting the thermal cycle of the hot gases expected within the fire enclosure. For further guidance, see Clause 9.

6.6 Time to onset of flashover

The onset of flashover indicates the change of fire conditions from a regime of growth to a regime of steady burning prior to decay. The time to onset of flashover may be quantified using sub-system 1.

6.7 Duration of steady burning

The interval between onset of flashover and commencement of decay is termed the duration of steady burning. It is during this period that the capacity of the enclosure to contain fire and the maintenance of structural function is challenged most. The duration of steady state burning is often characterized as the period over which, the fire load within the enclosure is reduced from 80 % to 30 % of its initial value, see sub-system 1.

7 Outputs

7.1 Introduction

The relationship between the outputs from sub-system 3 into the other sub-systems is shown in Figure 5.

7.2 Building characteristics

Analysis undertaken in this sub-system may conclude changes to the enclosure boundaries, e.g. failure of surfaces, opening of gaps, or alteration to the structural form, e.g. deflection or collapse of load-bearing elements of structure. These changes in the characteristics of the building need to be evaluated in their own right as part of the QDR process. The changes might also need to be considered as variable boundary conditions when analysing adjacent enclosures within the building.

7.3 Time to fire spread from enclosure

The QDR will establish what constitutes spread of fire from the enclosure of origin. The analysis described in this sub-system determines the time at which ignition of a fire occurs in a space or enclosure outside the enclosure of fire origin. In addition, guidance is given that allows the conditions generated outside the enclosure by a fire inside the enclosure to be determined, e.g. the extent of heat radiated from openings. These conditions (and their changes over time) may need evaluation in their own right as part of the QDR where they may affect other fire safety issues, e.g. the movement of persons within the building.

7.4 Time to structural failure

Establishing what constitutes failure of the structure can be determined by the QDR in accordance with PD 7974-0. Depending on the overall objectives, failure can range from collapse of a major structural element to an excessive deflection of a secondary member. In general, where the overall design objectives relate solely to the life safety of the buildings occupants, a larger degree of structural movement may be accommodated than, say, in those designs where the key objective is to observe a maximum level of damage and financial loss. For example, recent research by Corus, formerly British Steel plc, Swinden Technology Centre [2] has shown that continuous building frameworks are potentially capable of maintaining stability despite the loss of strength of individual beams or columns. Mindful of disproportionate collapse issues, the question as to whether local buckling of a column or the loss in load bearing capacity of a floor beam with associated deflections of the floor slab, constitutes failure in a building which remains stable in all other respects, is a matter of resolution with the QDR exercise. The time to structural failure can only be quantified if failure has been adequately defined within the QDR.

8 Analysis of mechanisms of fire spread

8.1 Forms of analysis

The potential for spread of a fire from its enclosure will be influenced by the thermal and mechanical response of the enclosure's boundaries (walls, roof, doors, windows). The thermal and mechanical response of boundary elements may be evaluated individually, subject to checking for interaction effects between adjacent elements. For example, the thermal bowing of walls may affect the support or loading conditions on the roof enclosure.

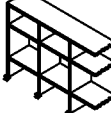
The behaviour of any individual element may be determined by:

- a) standard fire resistance tests;
- b) experimental large and small-scale fire tests;
- c) expert assessment;
- d) quantitative analysis of fire spread mechanisms.

The state of the art differs for each of the fire spread mechanisms. Certain mechanisms are best analysed through practical tests, whilst others may be analysed using reasonably advanced modelling techniques. It is important, when using engineering calculations to recognize the level of sophistication being employed. Table 1 summarizes the available forms of analysis. Maintaining a consistency of sophistication when evaluating the thermal and mechanical response as suggested in Figure 7 will increase the design efficiency.

Analysis of mechanical response

Analysis of thermal response

	Standard tests	Experimental tests	Expert assessment	Engineering calculations		
				 Single element	 Sub-frame	 Entire structure
Standard curves 	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Experimental curves 	✗	✓	✗	✓	✓	✓ (R,I) Note 1
Time Equivalent 	✓	✗	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Predicted Maximum temperature 	✗	✗	✓ (R,E,I)	✓ (R,E,I)	✓ (R,E,I)	✗
Predicted temperature curves 	✗	✗	✗	✓	✓	✓ (R,I) Note 1

NOTE 1 Integrity (E) is difficult to determine by calculation.

NOTE 2 R is the load bearing capacity criterion;

E is integrity criterion;

I is insulation criterion.

Figure 7 — Appropriate combination of various forms of analysis

Table 1 — Overview of means of analysis for each fire spread mechanism

Mechanism	Standard tests	Experimental tests	Expert assessment	Engineering calculations
Conduction	BS 476-20 (Insulation criteria) (See 8.1)	Standard experimental procedures available	Suited to expert assessment from the results of fire tests	Steady state equations describing conduction are easy to use but are overly conservative for all but very lightweight materials. Transient conduction models require software solutions (typically finite element or finite difference) and are well established and verified. The need for temperature dependent material thermal properties such as conductivity poses practical limitations as the necessary data are difficult to obtain. Care should be exercised if applying models to materials likely to undergo phase change or degradation at elevated temperatures. Chemical or physical changes can be associated with exothermic or endothermic reactions.
Convection	BS 476-20 (Integrity criteria) (See 8.1)	<i>Ad-hoc</i> fire tests possible	Suited to expert assessment from the results of fire tests	If openings are known, the convection of hot gases may be modelled using various field and zone models. Such models are well established for pre-flashover fires, but their application to post-flashover fires requires more care. The opening of gaps or cracks is difficult to model in solid boundaries. Techniques permit prediction of differential movement in discontinuous boundaries, e.g. doorsets.
Radiation	BS EN 1363 (Radiation measurements)	Standard experiments and <i>ad hoc</i> fire tests possible	Generally requires full calculation	If openings are known, a range of well established and verified radiation models are available, e.g. DD ENV 1991-2-2.
Mass transfer	Not applicable	ENV 1187 standard test and <i>ad hoc</i> fire tests possible	Suited to expert assessment	Not applicable
Direct pyrolysis and reaction to fire	BS 476-20:1987 (Integrity criteria) (See 8.1) Sustained flaming on non-exposed face	Range of standard ignitability tests available	Suited to expert assessment based on knowledge of combustibility	Not available

8.2 Standard fire resistance tests

8.2.1 Introduction

Fire safety professionals in the UK and many countries undertake standardized fire tests to obtain unambiguous information on the ability of specimens to resist the spread of a post flashover fire when subjected to an agreed set of conditions.

The information obtained from standard fire tests is expressed in terms of the ability of the element in question to remain stable, including not producing excessive deflections, for a period of time. The structure should also remain impermeable to the passage of flames, smoke and hot gases, at least to the level deemed critical to prevent fire spread for that period. Finally, conductive heat transmission of the construction to the unexposed face should not be greater than that permitted by the risk analysis.

When using a prescriptive approach to ensure the suitability of a construction. This performance is measured using a standardized fire exposure test, known as a fire resistance test, where the three performance objectives are defined as; load-bearing capacity, integrity and insulation.

During the standard fire resistance test a single element of construction of limited size is exposed to a time/temperature regime that is widely and incorrectly, assumed as representative of a fully developed fire. Test methods exist for vertical and horizontal elements of a separating and non-separating nature with or without applied load. For use in the built environment, the fully developed fire should be characterized by means of a time/temperature condition in accordance with ISO 834-1. This is the basis of most national standards around the world including BS 476-20:1987 and there is extensive knowledge of the behaviour of constructions exposed to these specified conditions.

The temperature time condition specified in BS EN 1363-1 is expressed in the same manner as both ISO 834-1 and BS 476-20. However, the method of measuring the furnace temperature has been changed in the BS EN 1363 procedure to a device (plate thermometer) that has a greater thermal inertia to the device (thermocouple) used in BS 476 tests. This change effectively increases the thermal severity in the fire test furnace and as a consequence construction elements tested in accordance with BS EN 1363-1, BS 476-20 and ISO 834-1, will exhibit different results. Designers should be aware of the differences in test regime and their effect on individual building components, as it is not possible to define one single test method that represents the most severe test for all types of constructions.

For other fire situations, outside of the normal built environment, a suite of hydrocarbon curves exist that are designed to evaluate the resistance of the structure to exposure conditions related to an accident involving hydrocarbon based fuels, see BS EN 1363-2. Whilst these curves are not intended to be used for the built environment, depending upon the fire engineering analysis of the anticipated exposure conditions, they may be more appropriate to some fire engineered solutions than the standard ISO 834-1 exposure.

8.2.2 Application of results of standard tests

The information produced by standardized tests, such as BS 476-20:1987 and BS 476-22, is reasonably well understood by the fire safety industry, including designers, regulators and approving authorities. In most cases, this permits a rapid appraisal to be made of an elements ability to resist the spread of fire, and maintain structural function.

However, the use of information from standardized fire tests does not free the designer from the requirement to fully understand the relationship between the element of construction tested and the element that will exist in the actual building enclosure. Where there is a direct similarity between the test specimen and the product used on site, e.g. beams of equal dimension or doorsets of a tested size and configuration, the only uncertainties regarding performance arise from workmanship. Quality control measures and certification schemes seek to address this risk. Additional consideration should be given in those instances where the test specimen does not directly correspond with the building element. This issue frequently arises as building components tend to be larger in size or differently configured to those submitted for fire testing.

The maximum specimen size that is evaluated under standard test conditions is generally 3 m high $\times$ 3 m wide, although a 4 m span is used for evaluating horizontal elements. If standard test data are justified for use in support of the performance of different constructions then an expert analysis should be carried out on the test result to ensure its suitability for extrapolation. BS ISO/TR 12470:1998 (see 13.4) describes how the extended application can be performed.

The performance of the construction when evaluated by the standardized fire resistance test is adjudged by three pre-determined criteria: loadbearing capacity, integrity, and insulation. In the case of loadbearing capacity, collapse is obviously the ultimate form of failure, about which case there is little question of interpretation. However, an alternative method of adjudging loadbearing capacity is by exceeding pre-determined deflection limits. These are rather arbitrary in nature and it could well be that they may be exceeded without necessarily causing fire spread. It should be recognized, however, that satisfying the fire resistance requirement with respect to loadbearing capacity for a period does not infer that the construction is free from any deflection. Significant levels of deflection are permitted by BS 476-20:1987 failure criteria. If the occurrence of deflection is important to the overall design, e.g. through influencing the performance of corridors forming protected routes on floors below deflected slabs, more restrictive deflection limits may be appropriate.

8.2.3 Determining the integrity (E) of elements

The integrity criterion used in the standard fire resistance test is one of the most difficult to translate into a fire engineering analysis of fire spread. Collapse is the ultimate loss of integrity, but there are varying degrees of integrity loss that are measured by other criteria. The alternative methods used are by means of an oven dry, cotton fibre pad placed 25 mm away from any gap or crack that is developing, or exists in the construction being tested, or by means of two sizes of gap gauges.

The cotton pad has been deemed inappropriate to use when there are high levels of radiation being emitted from the surface, i.e. when the insulation characteristics have been lost, because the pad can ignite as a result of the radiation and not the egressing gases. There are two gap gauges that are used in these situations. The 6 mm diameter gauge has to be able to be moved more than 150 mm before an integrity loss is registered, while the 25 mm diameter bar just has to pass through the element. These gauges are rigid and it is a requirement of BS 476-20 that they have to pass right through from the unexposed face to the exposed face before failure is recorded, and therefore labyrinth gaps can prevent this from occurring. It is quite possible for a 200 mm × 25 mm cross-sectional area gap to exist in a construction, but still be deemed to satisfy the integrity criterion if there is a convoluted path that prevents the gap gauge from passing right through the element. The risk of fire spread as result of a loss of integrity is very different when measured by these three methods, and this needs to be recognized when using integrity as a performance criterion.

8.2.4 Influence of pressure differentials on integrity

Another aspect of integrity measurement is that the test is performed with a pre-determined level of positive over-pressure, relative to the laboratory environment in the upper sections of the furnace. This is invariably where failure would be recognized by means of the cotton pad method. The positive pressure is used to monitor all separating elements and there are a number of situations where this is inappropriate. For example, when establishing the fire resistance of an external wall from the outside to the inside of a building, the need to resist a positive pressure is one of the most demanding aspects of the fire resistance test, except for largely impermeable constructions such as concrete. As a consequence, if positive pressure is not applied then the duration for which integrity is satisfied may be extended. Other situations where the positive pressure is inappropriate include the evaluation of enclosure walls after the roof has been lost.

It can be seen therefore, that the standard integrity criterion is difficult to apply directly to a fire engineering assessment of fire spread and in many cases may be considered to be excessively conservative if a purely life safety case is being produced. The proximity of combustible materials, and the sensitivity of equipment being protected also need to feature in the final analysis.

8.2.5 Insulation criteria (I)

The insulation criteria of the standard test consists of a maximum temperature rise of 180 °C anywhere on the surface and a mean temperature rise of 140 °C. These limits can be perceived as being excessively safe, although this will vary depending upon the fire safety objective. If there is a risk of people coming into contact with surfaces at these temperatures they are capable of providing significant burns, being well above those temperatures that skin contact can resist. However, if the objective of these limits is to reduce heating of the environment, or even igniting materials that might be in contact with them, then the temperature levels that have traditionally been set are probably somewhat lower than the environment can safely tolerate.

8.3 Experimental large and small scale fire tests

Experimental fire tests permit models or replicas of the elements to be exposed to a chosen heating regime within an experimental facility. The experimental facility may itself be designed on an *ad hoc* or project specific basis or may be an existing facility such as a standard fire resistance test furnace. The chosen heating regime might seek to simulate the anticipated fire conditions for the real building enclosure as predicted using fire models based on a worst case scenario (see Clause 9). Whilst designers on a project specific basis may commission experimental fire tests, the resources required make it more common for tests to be undertaken by research organizations on a building type basis or by industry on a product basis. Experimental techniques are available for measuring the thermal properties of materials using standard apparatus. Care should be taken to ensure that the properties obtained reflect the behaviour under transient heating conditions. In some cases, where there is no effect of heating rates, chemical or physical changes, then steady state test data may be appropriate.

Benefits may be accrued by increasing the scale of the experimental test, i.e. by minimizing the differences between the model and the prototype. The use of larger scale experimental fire tests means that the thermal and mechanical response of the element under examination may be deduced under boundary conditions that approximate to those expected in the real building configuration. For example, in experimental tests where levels of continuity and support can be accurately simulated, the observed behaviour will invariably be superior to that suggested in a lesser scale test or indeed than would be measured in standardized tests. Similarly, benefits may be accrued through accurate simulation of the thermal exposure anticipated for the element. For example, simulating the conditions that would prevail in reality through test replication of the actual fire load and ventilation conditions may offer rationality compared to standard furnace tests where conservative thermal conditions are assumed.

When setting up an experimental or semi-natural test, the designer should select the critical parameters of the test, e.g. fire load, ventilation, size of test chamber, construction of elements used to form the chamber, external environmental conditions, moisture content of hygroscopic materials. Such variables can have a significant influence on the outcome of the test and it is important that there is a stated relationship between the parameters chosen within the test and the anticipated conditions in the building that are to be modelled. In the written report describing the experiment test, all relevant parameters should be described and justified. This information assists the fire engineer in analysing the data and applying the information to design.

Scale modelling is one of the most difficult aspects of any fire simulation. Most semi-natural tests will be smaller than the assembly that is being replicated. This might not be so in respect of the actual volume of the fire enclosure, but if this space is within a larger structure, then it is quite likely that the actual constructional elements would be subjected to greater levels of restraint by their connection with elements outside of the fire enclosure. Similarly, they may be of a cross-sectional area, or a loading condition that cannot be properly simulated at the reduced scale. As a consequence, most semi-natural tests tend to incorporate a compromise in respect of some of the critical structural parameters.

In the case of fire exposure simulations, scale modelling is usually more difficult than it is in ambient testing because the effect of fire itself cannot be easily scaled. Whilst in mechanical tests it is possible to use a reduced load on a reduced cross-section and achieve a reasonably good prediction of what the capacity would be on a larger section, assuming that the material is generally homogenous, fire cannot be modelled in such a simplistic way. The thermal inertia of the section is critical as is the heat transfer rate to the surface of the item being heated. Flames unfortunately resist any attempt to model them. Whilst reduced fire loads can be used and it may be possible in some cases to alter the size or volume of the material being burnt, if the reaction is a flaming reaction, then almost all flames will behave in a similar way. The proportion of radiation with respect to convection varies with temperature and this cannot be altered easily. Consequently, heating as a direct result of flaming combustion almost defies any attempt to reduce its scale. This generally means that meaningful data can only be generated using structural sections with a similar thermal inertia and heat transfer coefficients to the sections being designed.

8.4 Expert assessment

Available data regarding the fire performance of generic boundary elements, obtained from reliable sources such as the results of standard fire resistance tests or accepted codes of practice, may be evaluated by competent persons to permit assessment of the likely performance of the element within the real building. The results of fire tests may be interpreted and extrapolated for practical applications in accordance with BS ISO/TR 12470:1998.

Understanding the effect of the difference in scale between the tested specimen and the real building component is one of the most difficult aspects of any expert assessment. In many cases, elements used for fire tests will be smaller than the building element that is being replicated. The change in scale can apply with respect to dimensional changes, such as height, width, cross-sectional area, or for boundary conditions, applied load and restraint.

In standard tests or specific simulated fire exposure conditions, scaling is more difficult to achieve than material tests carried out at ambient temperature. This is because the thermal effect of fire itself cannot be easily scaled. Whilst in mechanical tests it is possible to use a reduced load on a reduced cross-section and achieve a reasonable good prediction of performance under stress, fire cannot be modelled in such a simplistic way. The thermal inertia of the section is often critical as are the rate of heat exchange at its surface and the occurrence of flaming. The proportion of radiation versus convection varies with temperature and cannot be easily altered, consequently heating and in particular, direct flaming and combustion, are almost impossible to model at reduced scale. The effect of thermal expansion might not be fully realised at the scale of the specimen being subject to a fire test.

Expert assessments of the effects of differences between tested elements and real building components, including the effects of scale, should normally be underpinned by appropriate engineering calculations undertaken by competent persons. The basis of expert assessments should be documented as part of the reporting regime required by the QDR.

8.5 Quantitative analysis of fire spread mechanisms

8.5.1 Introduction

Each of the component mechanisms of fire spread may be quantified using engineering models and analysis. However, the level of sophistication available and the reliability of the results achieved vary widely amongst the different mechanisms. This reflects both the state of the art and the level of analysis typically required for practical design purposes.

8.5.2 Quantitative analysis of heat flow by conduction

The imposition of heat flux to one side of a boundary (the exposed side) will cause a temperature gradient through the body of the boundary surface to the unexposed surface where the boundary material is homogeneous. Fourier's Law states:

$$q_{\text{cond}} = -KA_e \frac{dT}{dN} \quad (11)$$

$\frac{dT}{dN}$ is the temperature gradient in the direction orthogonal to the area (K/m).

The negative sign indicates that heat will always flow from hotter to cooler surfaces. Heat will cease to flow between areas of the material that are at equal temperatures. Under steady state conditions where no internal heat is generated, the Laplace equation can be used, where:

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2} = 0 \quad (12)$$

where:

x, y, z are the orthogonal directions.

The general equations of conduction may be solved numerically for any particular application using for example finite difference or finite element techniques. In some special cases exact solutions are available and these may be employed, such as calculating the temperature rise in semi-infinite plane wall exposed to steady heat flux as described in 8.5.4. However, solution of the governing equations for applications in fire safety design is often problematic due to the transient heat flux imposed and the temperature dependency of the thermal diffusivity. Designers should take care to recognize the additional resources required to model transient conduction into enclosure boundaries and in particular, should avoid use of ambient heat flow techniques and ambient material properties, i.e. U-value methods.

A range of proprietary computer software is available to allow solution of transient conduction into solid members [3].

For solid homogeneous materials, it is possible to calculate the unexposed face temperature rise if the conductivity of the material is known, together with the gas temperature of the enclosure and a knowledge of the heat transfer coefficients of the material. The calculation is simpler if the temperature of the exposed face is known, as a result of semi-natural testing against the appropriate exposure conditions.

If the construction is non-homogeneous, then it is unlikely a calculation model exists that would enable the unexposed face temperature to be calculated with any accuracy. In these situations, the unexposed face temperature can only be established by measurements undertaken during a test in order to provide effective values under well defined heating conditions. This approach is particularly important where changes in physical properties result in endothermic or exothermic reactions. In cases where good contact between components forming a composite can be maintained at elevated temperatures, then the thermal behaviour may be established using reduced scale specimens. Where delamination at elevated temperatures is likely, unexposed face temperatures may only be established by exposing large specimens to fire. The only standard tests that are available for establishing these measurements are the fire resistance tests based upon BS 476-20:1987 or BS EN 1363-1.

It should be noted that the fire resistance test represents only one possible fire scenario and exposure conditions, and hence in reality unexposed face temperatures may vary from those measured against these conditions. It is also possible the thermal properties may be influenced by the rate of heating.

Based upon a knowledge of the quantity of heat being conducted through the body of an enclosure boundary, it is possible to quantify the temperature at any location through its thickness including the temperature on the unexposed surface. The unexposed surface is outside the enclosure of fire origin and its ignition constitutes fire spread.

Predicting the occurrence of ignition is an inexact science and is typically reliant on small-scale experiments that may not be readily scalable to real building assemblies. In the first instance it may be assumed that fire spread will not occur if the temperature rise on the unexposed face remains below 180 °C at all locations and below 140 °C as a mean. These temperatures represent those used as the failure criteria in BS 476-20:1987 for heat flow to the unexposed face of the test specimen. The origin of the limiting temperatures is unclear but they probably relate to temperatures observed for pilot ignition of wood. These criteria have been used to define insulation failure in standard fire resistance tests for many years and their adoption gives the designer some assurance that a conservative solution has been reached.

In fact, persistent ignition of the unexposed face requires a sufficient quantity of heat being conducted through the system at a rate in excess of its surface cooling such that the temperature rise of a minimum thickness is raised to a level in excess of the material's characteristic pyrolysis temperature. Most organic solids undergo pyrolysis in the range of 275 °C to 375 °C. Polymeric materials are susceptible to decomposition and undergo pyrolysis in the range of 200 °C to 400 °C (see Table 2).

Table 2 — Flash-ignition temperatures

Material	Flash – ignition temperature °C
Polyethylene	340
Polypropylene	320
Polystyrene	350
PVC	390
PTFE	560
Polyacrylonitrile	480
Polyurethane (rigid form)	310
Cotton	210

It is important to recognize that ignition temperatures are not an intrinsic property of materials. Ignition temperatures are affected by orientation of the material, its size, convection patterns, gas mixing and the presence of pilot flames. At best, ignition temperature should be viewed as an extrinsic material property and the designer should take great care when contemplating ignition temperature values in excess of 200 °C.

8.5.3 Quantitative analysis of heat flow by convection

The flow of heat from the enclosure of fire origin through fixed openings is described in PD 7974-2. However, many of the methods described are inappropriate to describing heat flow from post-flashover fires or from small and irregularly shaped openings such as might be created during a fire.

In general terms, the rate of heat flow from the enclosure of fire origin can be calculated by:

$$q_{\text{conv}} = MC_g(T_g - T_0) \quad (13)$$

The mass flowrate of gas from the enclosure will be a function of the area of the opening through which flow is taking place. For post-flashover fires, it may be conservatively assumed that M has reached a steady value of:

$$M = 0.5 A_w \sqrt{h_w} \quad (14)$$

PD 7974-2 offers guidance on how to predict the temperature of hot gases given information on their convective heat content and their mass flow rate. Clearly the temperature of the gases existing through the opening from the enclosure will decrease as the distance from the opening increases. Guidance for predicting the temperature of flames issuing from openings is given in 9.4.4.

The decision as to whether gases introduced at a given temperature into the space adjacent to the fire enclosure would cause ignition will remain project specific (see PD 7974-1). As explained in 8.5.2, the ignition of materials is difficult to predict. However, a broad range of natural and organic synthetic solids can undergo spontaneous ignition when heated to 500 °C and immersed in a hot gas plume, i.e. when heated by convection only. The presence of a pilot ignition source could precipitate ignition of the solids in the temperature range of 400 °C to 450 °C.

Although not strictly a criterion for fire spread, designers may also wish to note that humans cannot respire in saturated air environments at temperatures greater than 60 °C. In environments with less than 10 % water (by volume) humans cannot tolerate temperatures in excess of 120 °C for more than 7 min or 180 °C for more than 1 min. The development of gas temperatures of this magnitude may constitute an unacceptable spread of the effects of fire rather than ignition and actual fire spread. These issues should be agreed within the QDR process prior to establishing the criteria for deciding the propensity for convective fire spread.

8.5.4 Quantitative analysis of heat flow by radiation

A fire within an enclosure burning at a temperature, T_g , will radiate heat at a rate which can be calculated by:

$$q_{\text{rad}} = \varepsilon_g \sigma T_g^4 A_{\text{rad}} \quad (15)$$

The magnitude of the radiative heat flux falling on any surface outside the enclosure of fire origin is a function of several variables. These include:

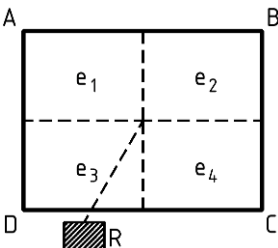
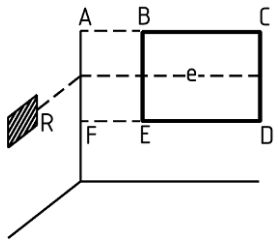
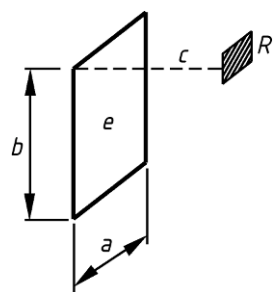
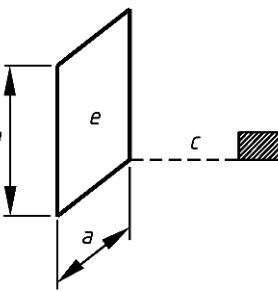
- the relative positions of emitting and receiving surfaces;
- the emissivity of the emitting and receiving surfaces;
- the temperature of the receiving surface.

Accordingly, the surface material of the receiver and its location will govern the level of radiation exposure outside the fire enclosure. Guidance is given in 10.2 on how the effects of radiation may be quantified for different materials.

In many cases, it will be possible to meet the design objective of examining radiative fire spread potential using a simplified approach. If it is assumed that the emitting and receiving surfaces have emissivity values of unity and that the receiving surface does not increase in temperature continuously over time (i.e. adopting a lumped approach), the radiative flux may be characterized as;

$$q_{\text{rec}} = F_{\text{e-Rqr}} \quad (16)$$

Figure 8 describes some commonly used configuration factors. Designers should note carefully the relative locations of the emitting and receiving surfaces and recognize the need to combine configuration factors for most practical applications.

Geometry	Configuration factor, F_{e-R}
 a)	$F_{ABCD-R} = F_{e1-R} + F_{e2-R} + F_{e3-R} + F_{e4-R}$
 b)	$F_{e-R} = F_{ACDF-R} - F_{ABEF-R}$
 c)	$F_{e-R} = \frac{1}{2\pi} \left\{ \frac{X}{\sqrt{1+X^2}} \tan^{-1} \left(\frac{Y}{\sqrt{1+X^2}} \right) + \frac{Y}{\sqrt{1+Y^2}} \tan^{-1} \left(\frac{X}{\sqrt{1+Y^2}} \right) \right\}$ where $X = \frac{a}{c}$ $Y = \frac{b}{c}$
 d)	$F_{e-R} = \frac{1}{2\pi} \left\{ \tan^{-1} \left(\frac{1}{Y} \right) - A Y \tan^{-1} A \right\}$ where $X = \frac{a}{b}$ $Y = \frac{c}{b}$ $A = \frac{1}{\sqrt{X^2 + Y^2}}$
Figure 8 — Configuration factors for typical scenarios	

A range of convenient methods have been developed to allow evaluation of the potential for radiative fire spread between openings from an enclosure and a parallel plane some distance removed. The enclosing rectangle method and the notional aggregate area method are described by Read [4]. These methods seek to ensure the maximum radiation received by any point in a plane parallel to the openings will not exceed 12.6 kW/m². The methods are typically employed in determining space separation distances between buildings and site boundaries with the minimum distance recommended as being halfway between the opening and the plane at which the incident radiation is 12.6 kW/m².

It should be noted that these methods are also applicable to evaluation of the radiation emitted from the hot unexposed face of an enclosure. This may assist in determining a limiting temperature for the unexposed face of enclosures (see 10.5.1). For analysis purposes T_g in equation (15) should be replaced by T_{surface} , the temperature of the unexposed surface (in kelvins).

It is difficult to state accurately what level of incident radiation is required to cause ignition of combustible items outside the enclosure of fire origin. Experimental studies have been limited to relatively small scale specimens. Furthermore, there is the complication as to whether pilot ignition is present in addition to the radiative flux, as for example that which can occur as a result of burning brands being emitted from the fire. Lawson and Simms [5] suggest that fibre insulation board will ignite under an incident flux of 24 kW/m². They also found that corrugated cardboard would spontaneously ignite under a radiative heat flux of 17 kW/m². Accepting the need for some factor of safety in design it appears that the widely used threshold of 12.6 kW/m² is reasonable.

Assessment of more accurate radiation thresholds for ignition may be possible based on an analysis of the increase in surface temperature of the object exposed. Kanuray [6] suggests that natural and synthetic organic solids will undergo spontaneous ignition under radiation when surface temperatures reach 600 °C. The presence of pilot ignition, e.g. flying brands, will reduce the threshold surface ignition temperatures to between 300 °C and 410 °C.

Whilst material specific guidance on the calculation of the thermal response of materials, is given in Clause 10, a useful surface temperature model for ignition hazard analysis is given by:

$$T(x, t) = T_0 + \frac{\epsilon_{\text{rec}} q_r}{\alpha_c} \left[e_{\text{rfc}} \left\{ \frac{0.5x_s}{\sqrt{Kt}} - \exp(\alpha_c x_s + K\alpha_c^2 t) \right\} e_{\text{rfc}} \left(\frac{0.5x_s}{\sqrt{Kt}} + \frac{\alpha_c}{k} \sqrt{Kt} \right) \right] \quad (17)$$

where:

t is the time from start of exposure (s)

Equation (17) assumes that the exposed solid surface can be treated as semi-infinite and is exposed to a radiating hot gas, e.g. a flat ceiling above an opening.

In addition, the potential for a radiative heat flux to cause remote ignition and fire spread from the enclosure may affect persons outside the enclosure of fire origin to an unacceptable level. For example, people may not be able to escape past an opening from the fire enclosure because of excessive radiation. This hazard has been recognized in building design leading to protection of external openings adjacent to stairways and control of glazed openings onto corridors.

The acceptability of an incident radiative heat flux to humans is largely a function of the duration of cumulative exposure. People can sustain higher levels of radiation for short intervals. Table 3 offers some guidance on acceptable levels of exposure. The tenability issue is considered in PD 7974-5. The necessity of considering the spread of the effects of fire should be determined in the QDR exercise (see PD 7974-0).

Table 3 — Maximum permitted radiation dose to building occupants

Radiative heat flux kW/m ²	Duration of exposure s
< 2.5	> 300
2.5	30
10	4

8.5.5 Quantitative analysis of heat flow by mass transfer

The direct escape of fire from an enclosure by way of mass transfer of burning material is difficult to quantify. The mass transfer of hot gases from enclosures has been discussed previously in 8.5.3. It is possible that the transfer of burning solids or liquids from an enclosure via fixed or fire created openings will cause remote ignition and fire spread.

The escape of solid materials from the fire enclosure, e.g. flying brands, is difficult to predict with any certainty. The occurrence of such mass transfer can be important particularly in evaluating the ignition of combustibles outside the enclosure. As explained in 8.5.3 and 8.5.4, the ignition temperature of materials will be significantly reduced in the presence of a source of pilot ignition. In the absence of detailed analysis, designers should assume that mass transfer will occur and should conclude their ignition temperature thresholds accordingly.

The flow of burning liquids from the fire enclosure is likely to promulgate fire spread. The scenario can arise in enclosures containing stored combustible liquids. Designers should consider the potential fire spread mechanism where any liquid fuel is stored either independently in containers or within machines and engines.

Mass flow of burning liquids may be prevented through construction of a liquid retaining bund fully encircling the fuel supply. The height of the bund should be sufficient to contain the entire volume of liquid anticipated. Bunds should be impermeable to the passage of liquids and should be free of holes and service penetrations.

8.5.6 Quantitative analysis of heat flow by direct pyrolysis and reaction to fire

Continuous construction assemblies extending beyond enclosures, e.g. roofs, walls and ceiling slabs that are combustible may contain burning materials. The extent of burning will be a function of the construction material and its configuration. Quantifying these parameters is very difficult (see PD 7974-1).

A reasonable design approach is to assume that any combustible material within the fire enclosure will at some stage become involved in the fire. The nature, direction and spread of pyrolysis is indeterminate and accordingly it should be assumed that all combustible material becomes ignited. Any part of a continuous combustible construction that extends outside the enclosure should be viewed as permitting fire spread beyond that enclosure.

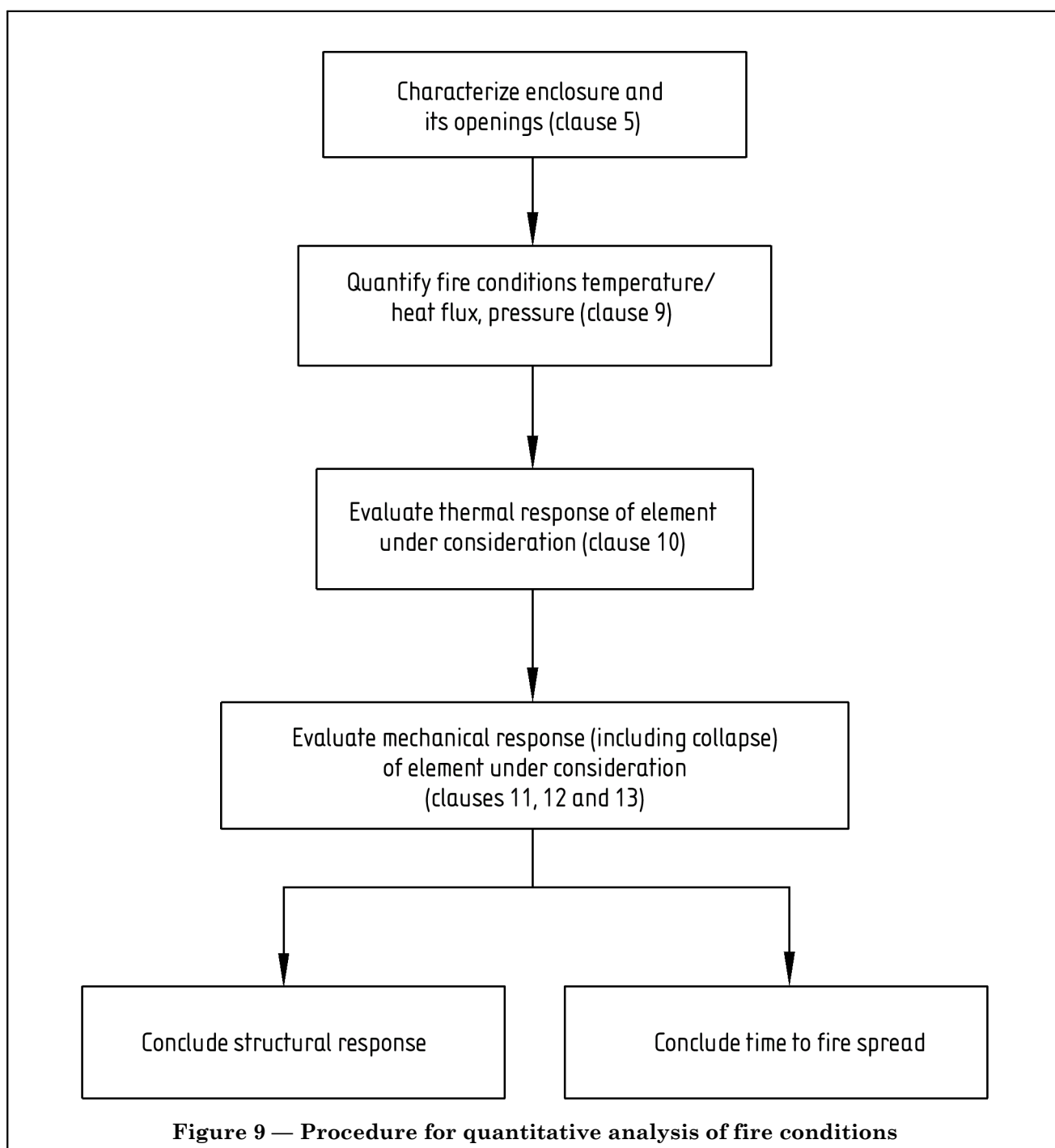
Traditionally this fire spread mechanism has not been subject to quantitative study, but rather is avoided through installation of fire stopping to break the continuous combustion path. An example is the fitting of non-combustible fire stopping within the body of a combustible roof system where it passes over an enclosure boundary. An alternative approach is to ensure that the continuous combustible path is not exposed to fire, say by protecting it with a non-combustible surface. The likelihood of fire spread by way of conduction may be evaluated in accordance with 8.5.2. However, attention is drawn to the integrity of the mechanical bond between the non-combustible surface and the combustible core, particularly at temperatures in excess of 150 °C. Robust mechanical connections can improve matters, subject to consideration of heat transfer by conduction.

9 Characterization of the fire conditions

9.1 Introduction

9.1.1 Forms of analysis

The fire condition within an enclosure is generally described in terms of either an air temperature/time profile or a total heat flux/time profile. The extent of detail required in the description of the fire condition will be influenced by the level of analysis subsequently to be employed. For example, the maximum temperature certain elements are exposed to determines their mechanical response. In such circumstances, details of the entire temperature/time profile within the enclosure are unnecessary once the maximum temperature is known. Figure 7 offers guidance on appropriate combinations of analysis methods for thermal and mechanical response. Figure 9 outlines the means of proceeding with the analysis.



9.1.2 Temperature based description of fire conditions

PD 7974-1 offers guidance for establishing the temperature/time behaviour of the fire. However, quantification of the fire conditions during the period of interest for fire spread (as opposed to life safety of occupants) is often considered separately using the following approaches:

- characterization of fire conditions using standardized models of fire (by fire type or occupancy type);
- determination of the fire conditions from experimental investigation;
- determination of the fire conditions through engineering calculations.

9.1.3 Heat flux based description of fire conditions

The total heat flux, q_{total} , produced under fire conditions, can be calculated by:

$$q_{\text{total}} = q_c + q_r \quad (18)$$

The fire temperature and the nature of the fuel being burned largely determine the relative magnitude of the convective and radiative heat fluxes.

9.2 Characterization using standardized models of fire (by fire type or occupancy type)

9.2.1 Standard temperature/time relationship

PD 7974-1 describes the use of standardized fire curves to describe the temperature/time development of fires in enclosures prior to flashover in terms of slow, medium, fast or ultra-fast growth. In post flashover conditions, alternative standardized temperature/time relationships should be employed. It should be noted that these standardized temperature/time relationships have largely originated from furnace fire test methodologies and do not necessarily represent real fire conditions within an enclosure.

A standard temperature/time fire model used to characterize fires in enclosures containing typical cellulosic contents can be calculated by:

$$T_g = 20 + 345 \log_{10}(8t + 1) \quad (19)$$

where:

T is the time from ignition (min).

The fire model described by equation (19) is the basis of fire resistance tests undertaken to BS 476-20:1987, BS EN 1363-1, BS EN 1363-2 and ISO 834-1.

9.2.2 Hydrocarbon temperature/time relationship

A temperature/time fire model used to characterize more severe fires in enclosures containing hydrocarbon based contents (see BS 476-20:1987, Annex D) can be calculated by:

$$T_g = 1100\{1 - 0.325\exp(-0.1667t) - 0.204\exp(-1.417t) - 0.471\exp(-15.833t)\} \quad (20)$$

The fire model described in equation (20) is very similar to that specified in DD ENV 1991-2-2.

9.2.3 External temperature/time relationship

A temperature/time fire model used to characterize less severe fires immediately outside typical enclosures, and emanating from within the building e.g. the condition of flames issuing from adjacent windows, can be calculated by:

$$T_g = 660\{1 - 0.687\exp(-0.32t) - 0.313\exp(-3.8t)\} + 20 \quad (21)$$

9.2.4 Smouldering temperature/time relationship

A temperature/time fire model used to characterize the first 20 min burning of a smouldering fire can be calculated by:

$$T_g = 154 t^{0.25} + 20 \quad (22)$$

This curve should be followed by the standard curve, described by equation (19), for a further 20 min. Note, however, this type of heating curve was developed so that materials such as intumescent coatings which rely upon chemical reactions could be subject to a test that addressed possible concerns regarding their intumescent behaviour. It was not meant to represent a design fire scenario.

9.2.5 Characteristic design fires by occupancy

Over the years a range of experimental fires have been observed in realistic simulations of typical building premises. Interpreting the test results may inform designers as to the anticipated fire conditions in typical occupancies, such as offices, car parks, etc. Adopting such design fires may be reasonable where the enclosure in question is well represented by the underlying experimental set-up particularly with regards to:

- fire load density;
- nature of the fire load;
- extent of ventilation;
- ceiling height;
- thermal properties of the enclosure.

9.2.6 Duration of fire to be adopted in design

The relationships described in 9.2.1 to 9.2.4 are continuous and make no statement as to the duration such conditions are assumed to exist. Clearly, all fires have a finite fuel supply available to them. Once the fuel is exhausted, the fire will decay, conditions will become less severe and the fire will eventually extinguish. Whilst the amount of fuel or fire load present is an important variable in determining fire duration, so too is the burning rate of the fire. This is influenced by variables including the extent of available ventilation and the thermal properties of the enclosure.

Characterization of the fire conditions in terms of a chosen standardized temperature/time profile for a set duration is a key design decision in determining the propensity for fire spread. It should reasonably reflect less quantifiable concerns such as the risk of a post-flashover fire actually occurring within the enclosure and the consequences of fire spread. For this reason, recommendations on the design duration of standardized fire conditions are given in a range of codes of practice and regulatory documents.

Attention is drawn to the following statutory regulations:

The Building Regulations (England and Wales) 2000 [7];
 The Building Standards (Scotland) Regulations 1990 [8];
 The Building Regulations (Northern Ireland) 1990 [9].

The appropriate duration of the standard heating curve, described in equations (19) to (22) is influenced by parameters such as:

- a) nature of occupancy of the enclosure;
- b) presence of automatic sprinkler system;
- c) height of enclosure above ground level;
- d) depth of enclosure below ground level.

Alternatively, the design duration of the standardized fire conditions described in 9.2.1 may be determined by engineering calculation of the time-equivalent value as described in 9.2.4.

9.3 Determination of fire conditions from experimental investigation

Various full-scale or large scale fire experiments have been performed in realistic building enclosures [2], [10] to [19]. These can provide information on the complete temperature/time profile for fires in certain enclosure types, which may assist fire engineers in the analysis of comparable enclosures. They have predominantly used either timber cribs or actual building contents as the fuel source.

Alternatively, the fire engineer may design and commission appropriate experimental fire tests to model a particular enclosure scenario, observing as appropriate the principles set out in BS 6336 and/or BS 476-33. Demonstrably competent persons or bodies such as research institutions and test laboratories only should undertake experimental fire tests.

The results of *ad hoc* fire tests should be subject to careful evaluation before integrating them into the design process. As discussed with the use of standardized fire models, there is a similar need to consider less quantifiable factors relating to risk and consequence when arriving at a set of design fire conditions. Consideration of such factors could result in the application of safety factors to the observed fire temperature/time profile.

9.4 Determination of fire conditions through engineering calculations

9.4.1 Prediction of maximum fire temperature within enclosures

The temperatures developed in post-flashover fires is discussed in PD 7974-1.

The maximum temperature attained during a ventilation controlled fire within enclosures bounded by materials having a thermal inertia in the range of $720 \text{ J/m}^2 \cdot \text{s}^{1/2} \cdot \text{K}$ to $2\,500 \text{ J/m}^2 \cdot \text{s}^{1/2} \cdot \text{K}$ can be calculated by:

$$T_g^{\max} - T_o = 6000 \{1 - \exp(-0.10\eta)\} \eta^{-1/2} \{1 - \exp(-0.05\psi)\} \quad (23)$$

Equation (23) may be used with confidence for enclosures having thermal inertias in the range of $720 \text{ J/m}^2 \cdot \text{s}^{1/2} \cdot \text{K}$ to $2\,500 \text{ J/m}^2 \cdot \text{s}^{1/2} \cdot \text{K}$, e.g. blockwork, dense/lightweight concrete, plasterboard boundaries. It will generally deliver conservative predictions, overestimating temperature by up to 25 %. Where an enclosure is likely to experience a through draught condition from openings on opposing walls, the temperatures attained within the enclosure will be lower as determined by the relationship:

$$T_g^{\max} - T_o = 1200 \{1 - \exp(-0.04\psi)\} \quad (24)$$

9.4.2 Characterizing transient fire conditions within enclosures

A heat energy balance equation can be used to predict the temperature/time profile of the hot gases within an enclosure represented by equation (25):

$$Q_{\text{total}} = Q_c + Q_w + Q_r + Q_g \quad (25)$$

Gas temperature/time curves have been derived relating to enclosures having average thermal properties (e.g. brickwork, blockwork, plaster) as a function of fire loading and ventilation. These relationships have been simplified to a group of descriptive equations given in DD ENV 1991-2-2.

The temperature of the fire gas, T_g in the heating phase can be calculated by:

$$T_g = 1\,325 \{1 - 0.324\exp(-0.2t^*) - 0.204\exp(-1.7t^*) - 0.472\exp(-19t^*)\} \quad (26)$$

where:

$$t^* = \Gamma \cdot t;$$

t is the time from ignition (h);

$$\Gamma = \left(\frac{o}{b}\right)^2 \left(\frac{1160}{0.04}\right)^2;$$

b is subject to the limit $1\,000 \leq b \leq 2\,000$, see 3.1.3;

O is subject to the limit $0.02 \leq O \leq 0.20$;

$$O = (A_w \sqrt{h_w}) / A_t (m^{1/2}).$$

The maximum temperature, $T_g^{\max}$, is reached after a time when:

$$t_{\max}^* = \frac{0.13 \times 10^{-3}}{O} q \cdot \Gamma \quad (27)$$

where:

$q = L/A_t$ subject to the limit $50 \leq q \leq 1\,000 \text{ MJ/m}^2$;

L is the total fire load in the enclosure (MJ).

The temperature decay at times beyond the time of maximum temperature can be calculated by;

$$T_g = T_g^{\max} - 625 (t^* - t_{\max}^*) \quad \text{for } t_{\max}^* \leq 0.5 \quad (28)$$

$$T_g = T_g^{\max} - 250 (3^* - t_{\max}^*)(t^* - t_{\max}^*) \quad \text{for } 0.5 < t_{\max}^* < 2 \quad (29)$$

$$T_g = T_g^{\max} - 250 (t^* - t_{\max}^*) \quad \text{for } t_{\max}^* \leq 2 \quad (30)$$

A programme of full scale natural fire tests reported by Kirby *et al.* [16], has found that the fire curve described in equation (26) underpredicts the fire temperatures developed in highly insulated enclosures. However more recent full scale fire tests conducted by Swinden Technology Centre has shown reasonable correlation for compartments constructed using materials more typical of those used in buildings such as concrete floors and lightweight concrete blockwork. In such applications, an earlier method developed by Pettersson *et al.* [1], showed improved correlation with the experimental data.

It is recommended that the enclosure fire models described in equations (26) to (30) should be used only for enclosures up to 400 m² in floor area. Beyond this size the assumption of uniform burning within the enclosure may become invalid. Similarly, compartments having openings in one face only and having a width to depth ratio in excess of 1:6 may also experience uneven burning. Further and more detailed consideration is required in such instances.

Equation (26) is amenable to developing solutions using computer software and has the attraction of producing a full temperature/time relationship histories for fully developed fires in enclosures. Nonetheless, the limitations described by Kirby *et al.* [16] persist and great care should be taken in the use of computer software based on these curves for highly insulated enclosures. Software solving equation (26) may be used more confidently in applications where the boundary conditions are 720 J/m²s^{1/2}K to 2 500 J/m²s^{1/2}K, i.e. similar to those conditions present in the test enclosure fires upon which models are calibrated. The designer should seek full details of model validation prior to its application for real building design and should be satisfied regarding suitability for purpose and the validity of its underlying assumptions.

9.4.3 Equivalent time of fire exposure

The anticipated fire conditions within the enclosure may be characterized with reference to a set duration of the standardized gas temperature/time relationship described in 9.2 and BS 476-20:1987. The duration of exposure has been derived empirically and is referred to as the equivalent time of fire exposure or “time equivalent” value.

- a) A number of researchers have proposed methods for correlating durations of exposure to real fires [20] to [22].

DD ENV 1991-2-2 suggests that exposure of boundary elements to the standardized fire conditions described in equation (18) for the time equivalent duration, represents an equivalent level of thermal exposure as would be experienced by exposure to the full duration of a fire within the building enclosure.

The duration of time equivalence, t_e , can be calculated by:

$$t_e = k_b w_v q \quad (31)$$

In the UK National Application Document (NAD) to DD ENV 1991-2-2, k_b may be assigned a value of 0.07 for enclosures bounded with typical building surfaces, e.g. masonry, gypsum plaster.

Building surfaces with high levels of insulation, e.g. proprietary wall insulation systems, may be allocated a k_b value of 0.09.

In other instances, k_b may be evaluated using Table 2.

Table 4 — Values of k_b

Thermal inertia, b J/m ² s ^{1/2} K	Minimum factor, k_b m ² /MJ
$b < 720$	0.09
$720 \leq b \leq 2\,500$	0.07
$b > 2\,500$	0.05

w_v is defined by:

$$w_v = 1.7 H^{-0.3} \{0.62 + 90 (0.4 - A_v/A_f)^4\} (1 + b_v A_h/A_f)^{-1} \geq 0.5 \quad (32)$$

b_v can be calculated by:

$$b_v = 12.5 \{1 + 10 (A_v/A_f) - (A_v/A_f)^2\} \geq 10 \quad (33)$$

Equation (31) has been shown through large scale fire tests to exhibit a reasonable degree of correlation with the behaviour of protected steel members observed in fire resistance tests [16]. For unprotected steel, more recent work by Kirby and Tomlinson [23], has shown the time equivalent relationship is valid for up to 40 min fire resistance, thereafter the relationship breaks down.

Whilst equation (31) is a reasonable predictor of enclosure fire conditions, it does not consider those less quantifiable influences on design fire duration (as discussed in 9.2.6). This shortcoming is addressed in the National Application Document (NAD) issued together with DD ENV 1991-2-2 for use in England/Wales, Scotland and Northern Ireland.

The design time equivalent duration, t_{ed} , can be defined as follows:

$$t_{ed} = \gamma_1 \gamma_2 \gamma_3 t_e$$

(34)

Suggested values for γ_1 and γ_2 are given in Table 5 and Table 6 respectively. In the absence of further analysis γ_3 may be taken to be 0.6.

It is conceivable that various enclosures within a single building are expected to be the subject of different time equivalent durations. Whilst this is not normal practice as reflected by regulatory documents (*The Building Regulations (England and Wales), Approved Document B, Fire Safety, 2000 Edition*, Department of Environment Transport and Regions, 2000; *The Building Standards (Scotland) Regulations* Scottish Office, 1990; *The Building Regulations (Northern Ireland)* Department of the Environment, 1990), it may be acceptable within an engineered framework [7], [8], [9]. However, the designer should maintain consistency in approach and ensure that all possible interactions between enclosures are considered. In particular the designer should ensure that boundaries or structural elements shared between enclosures are examined under the more onerous of the anticipated fire conditions.

Table 5 — Possible values for g_1 for use in equation (34)

Occupancy of enclosure	Safety factor, γ_1			
	Height of enclosure above ground level			
	≤ 5 m	≤ 20 m	≤ 30 m	> 30 m
	Depth of enclosure below ground			
		≤ 10 m	> 10 m	
Residential, institutional, offices	0.8	1.1	1.6	2.2
Assembly, shops	0.8	0.8	1.1	2.2
Industrial	0.8	0.8	1.1	2.2
Car parks	0.4	0.8	1.1	1.6

Table 6 — Possible values for γ_2 for use in equation (34)

Occupancy of enclosure	Safety factor, γ_2
Residential, institutional, offices	1.2
Other occupancies	0.8

The use of time-equivalent techniques for the characterization of fire durations in the context of analysing enclosure members other than steelwork needs further consideration. In particular its application to the consideration of materials that have a time based response to heating, e.g. concrete or timber, may be inappropriate as the method is founded on the temperature response of protected steelwork.

9.4.4 Characterizing the condition of fires from openings in enclosures

When examining the potential for convective or radiative fire spread from an enclosure, it may be necessary to characterize the shape, size and temperature profile of flames emerging from openings in the enclosure boundaries.

In the first instance, the fire may be assumed to completely fill the area of the opening, burning at a temperature not less than the gas temperatures assumed within the enclosure. When evaluating the potential for fire spread to surfaces outside the enclosure, the emissivity of the fire source should be taken as unity.

Another convenient, albeit conservative approach, is to assume that the entire area of the opening acts as a heat radiator. The level of radiation may be calculated from the enclosure gas temperatures or may be allocated notional values as shown in Table 7.

Table 7 — Notional radiation levels from openings in enclosures

Enclosure characterization	Radiation from opening kW/m ²
Residential, office, assembly, recreation or open-sided car parks	84
Shop, commercial, industrial, storage or other non-residential	168

More advanced analysis allows consideration of the failure of boundaries, e.g. glazing and the emergence of the fire through the plane of the boundary enclosure, i.e. flames issuing through openings. The flame height, width and its horizontal projection from the enclosure can be calculated in accordance with DD ENV 1991-2-2, using methods developed by Law and O'Brien [24].

The temperature and emissivity of the projecting flame front may be calculated using the same method. Whilst the method was developed to characterize flames issuing from external windows, it may also be used to define flames issuing from internal openings into larger spaces such as doors and windows into atria.

The flame envelope from an enclosure is defined as that area of emerging gases at temperatures of 540 °C and higher. In the absence of a through draught, the extension of flaming, Z , above the head of an opening can be described by:

$$Z = 12.8 \left(\frac{R}{w} \right)^{2/3} - h_w \quad (35)$$

The width of the flame projecting from an opening may be taken as being equal to the width of the opening, see Figure 10a). The depth of the flame front within the plane of the opening may be conservatively taken as $2/3$ of the opening height, i.e. $2/3 h_w$. This dimension is also assumed to define the thickness of the flame λ .

The horizontal projection of the flame away from the opening is governed by the ability of air to get behind the flame front. Accordingly where there is no wall above the opening or where the opening width is narrow, the centre of the flame tip will be projected from the plane of the opening a distance, x , where:

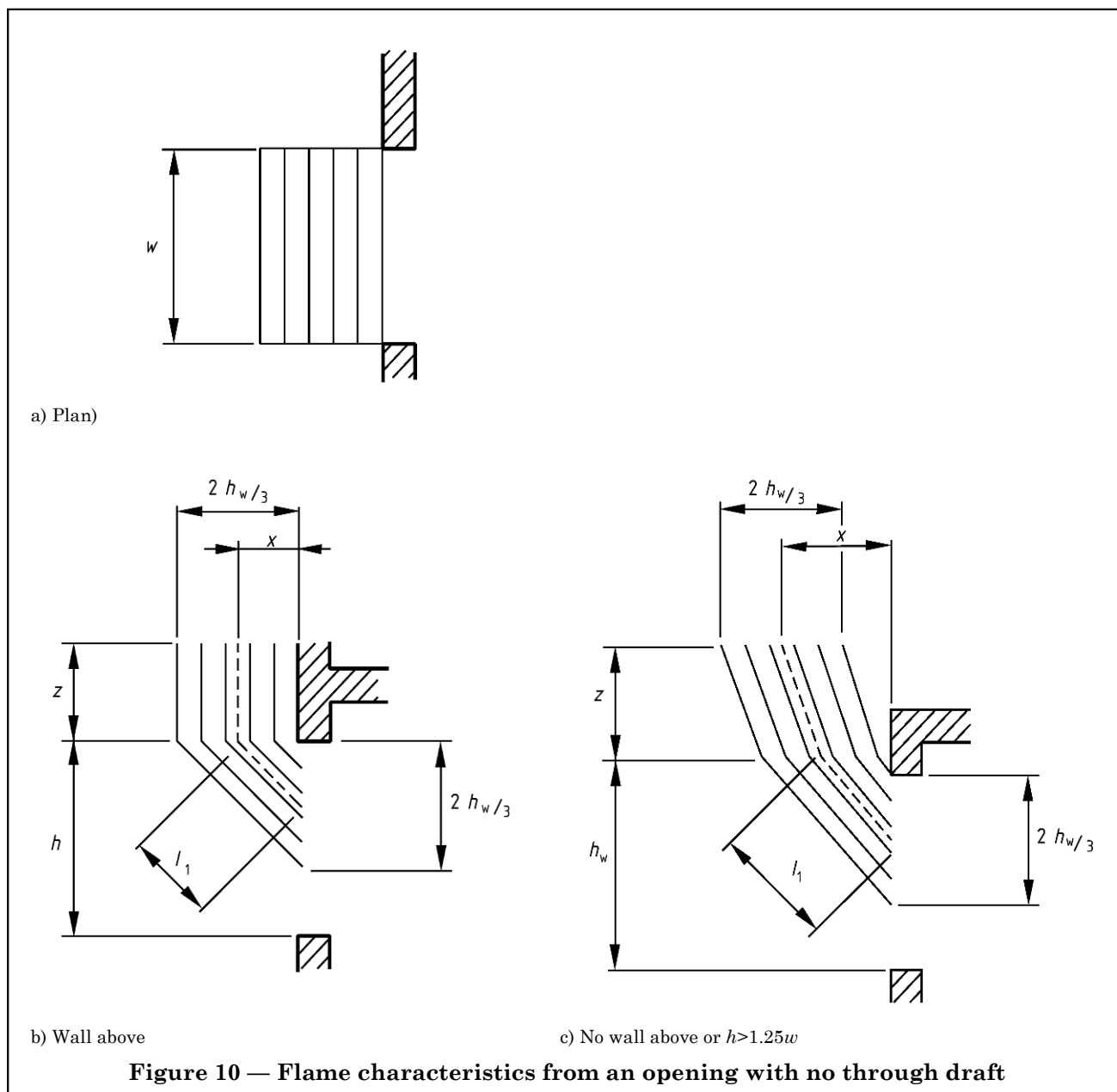
$$x = 0.6 h_w \left(\frac{Z}{h_w} \right)^{1/3} \quad (36)$$

When the opening is wide ($h_w < 1.25w$) or has a wall above it, the tip of the flame projection is $h_w/3$.

When $h_w > 1.25w$ and the distance to any other window exceeds four times the window width, projection can be calculated by:

$$x = 0.3 h_w \left(\frac{h_w}{w} \right)^{0.54} \quad (37)$$

It should be noted that the total projection of the flame envelope from the plane of the opening is $x + h_w/3$, see Figure 10b) and Figure 10c).



The length of the flame axis, X , from the plane of the opening to the flame tip can be described by;

$$X = Z + h_w/2 \quad (38)$$

where there is a wall above and $h_w \leq 1.25w$ or

$$X = \sqrt{Z^2 + (x - h_w/3)^2} + h_w/2 \quad (39)$$

where $h_w > 1.25w$

The flame temperature at the plane of the opening, T_{opening} , can be calculated by;

$$T_{\text{opening}} = \frac{520}{(1 - 0.027)(Xw/R)} - T_o \quad (40)$$