

PD 7974-3:2011



BSI Standards Publication

PUBLISHED DOCUMENT

Application of fire safety engineering principles to the design of buildings

Part 3: Structural response and fire spread beyond the enclosure of origin

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Summary of pages

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Foreword

Publishing information

This Published Document is published by BSI and came into effect on 30 November 2011. It was prepared by Technical Committee FSH/24, *Fire Safety Engineering*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This Published Document supersedes PD 7474-3:2003, which is withdrawn.

Information about this document

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 documents in the series are:

PD 7974-0: *Guide to design framework and fire safety engineering procedures;*

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

PD 7974-2: *Spread of smoke and toxic gases within and beyond the enclosure of origin;*

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

PD 7974-5: *Fire service intervention;*

PD 7974-6: *Evacuation;*

PD 7974-7: *Probabilistic risk assessment.*

Presentational conventions

The provisions of this Published Document are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

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

Contractual and legal considerations

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

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

Introduction

This Published Document is one of a series of documents intended to support BS 7974, *Code of Practice on the Application of Fire Safety Engineering Principles to the Design of Buildings*.

This and the other Published Documents (PDs) contain “state of the art” guidance and information on how to undertake quantitative and detailed analysis of specific aspects of design. It is intended that they be updated as new theories, calculation methods and/or data become available.

However, it is important to recognize that the information contained within PD 7974-3 does not preclude data, information or methods of analyses from other sources, such as published peer reviewed research, manufacturers’ data or codes of practice prepared on behalf of the construction materials industry, professional engineering and technical institutions and other professional bodies.

BS 7974 was first published in 2001. Since then there have been substantial changes in understanding in the behaviour of fire in the built environment and how materials and construction systems respond at elevated temperatures. Not least, the structural Eurocodes on Fire Actions have been published as full European Standards. These have resulted in revised formulations on the behaviour of structural components in fire, as well as new data on the thermal and mechanical properties of the various materials used in building construction. One of the most significant and recent advances in the understanding of buildings in fire has come about as a result of studies of experimental major fires in full size structures and the ensuing guidance this has generated on analysing the structural behaviour of the framework and compartmentation.

However, where understanding the behaviour of construction systems and building products cannot be quantified, or there are no specific analyses of some aspects of fire spread beyond the enclosure of origin other than the performance of products based upon a fire resistance furnace test, a commentary is given on the particular issues that need to be considered and how these could be treated.

A fire-safety engineering approach that takes into account the total fire safety package can provide a more economical solution than prescriptive approaches to fire safety. In some cases, it is the only viable means of achieving a satisfactory standard of fire safety in some large and complex buildings.

A major issue in the determination of the structural response is the application of time equivalent methods in specifying an equivalent period of heating in the standard fire resistance test furnace. Any outputs should consider the consequences of failure in relation to the particular occupancy and building dimensions (height and compartment size) and its location in the building, for example, BS 9999 specifies a risk-based approach for occupant life safety in building structures.

Fire safety engineering has many benefits. The use of BS 7974 facilitates the practice of fire safety engineering and, in particular:

- a) provides the designer with an organized approach to fire safety design;
- b) allows the safety levels for alternative fire safety designs to be compared;

- c) provides a basis for selection of appropriate fire protection systems;
- d) provides opportunities for innovative design; and
- e) provides information on the management of fire safety for a building.

Fire is an extremely complex phenomenon and there are still gaps in the available knowledge. When used by suitably qualified persons experienced in fire safety engineering, BS 7974 and its associated PDs provide a means of establishing acceptable levels of fire safety economically, without impeding building design.

For the purpose of this Published Document, spread of fire beyond the enclosure of origin is deemed to have taken place when any material outside of the fire enclosure ignites or suffers thermal degradation. Structural response is the interaction of loadbearing and non-loadbearing elements or frames as a result of thermal and/or mechanical actions due directly or indirectly to a fire. The level of sophistication employed to evaluate fire spread can vary. For example, a simple decision can be taken that the creation of any openings or gaps in the enclosure boundaries precipitates fire spread. Alternatively, more complex analyses can be employed to consider whether flames project from openings in the enclosure's boundaries and whether such flames ignite or degrade materials outside the enclosure.

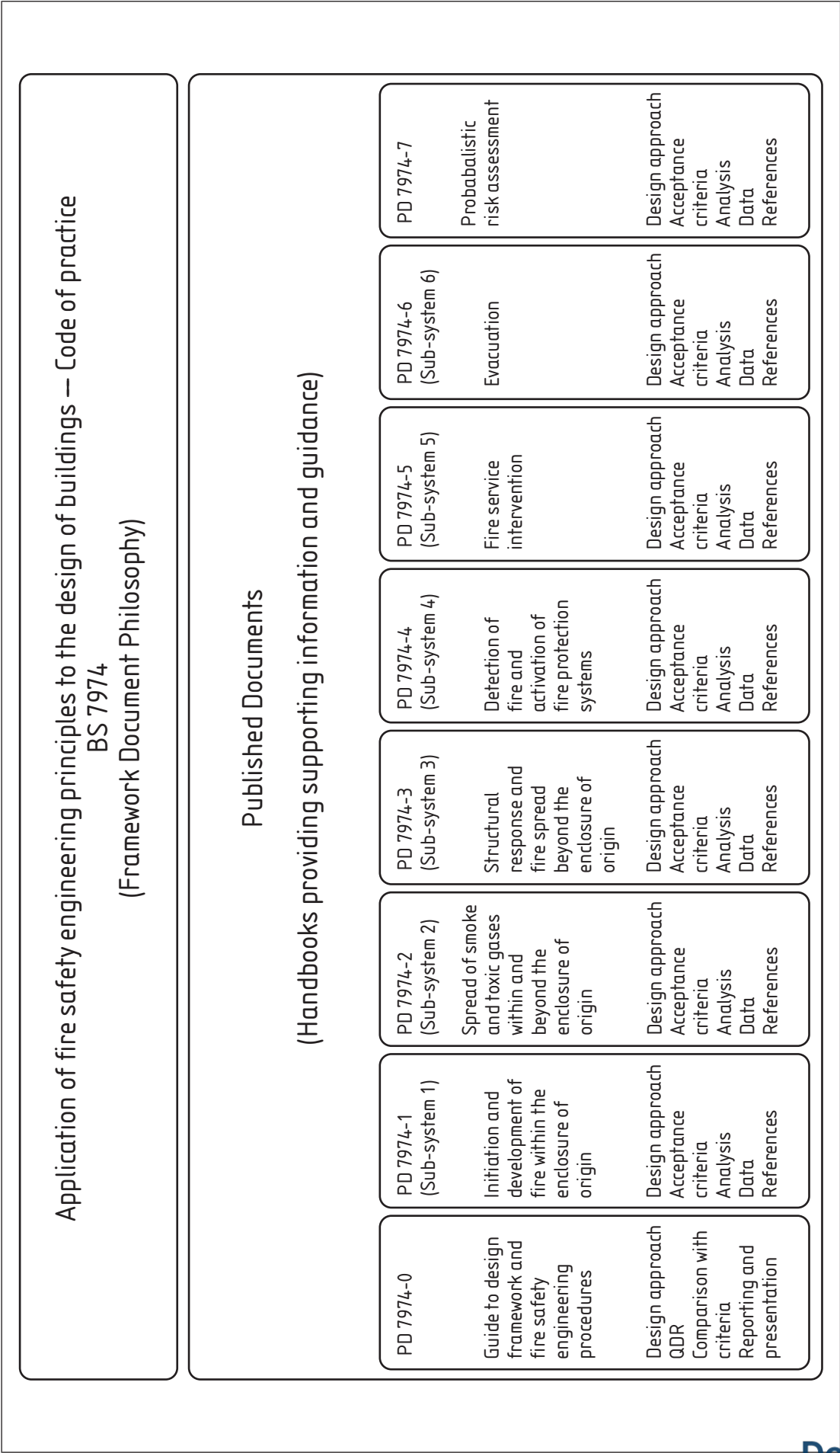
Throughout PD 7974-3 reference is made to relevant codes of practice. Where appropriate, relevant extracts are provided in order to assist the reader in understanding the design methodologies presented and to compare and contrast between different approaches or sources of data. It is therefore important that PD 7974-3 is not used in isolation and reference is made to the relevant codes of practice, particularly in relation to additional notes and sub-clauses describing its application (see Figure 1).

1 Scope

This Published Document provides a framework for developing a rational methodology for design using a fire safety engineering approach through the application of scientific and engineering principles to the protection of people, property and the environment from fire. The Published Document considers the following issues:

- a) the conditions within a fire enclosure and their potential to cause fire spread;
- b) the thermal and mechanical response of the enclosure boundaries and its structure to the fire conditions;
- c) the impact of the anticipated thermal and mechanical responses on adjacent enclosures and spaces;
- d) the structural responses of loadbearing elements and their effect on structural stability, load transfer and acceptable damage according to the design and purpose of the building;
- e) fire following structural impact to the building.

Figure 1 Overview of the PD 7974 series of Published Documents



2 Normative references

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

BS 476:1932, *British standard definitions for fire resistance, incombustibility and non-inflammability of building materials and structures (including methods of test)*

BS 476-3, *Fire tests on building materials and structures – Part 3: Classification and method of test for external fire exposure to roofs*

BS 476-4, *Fire tests on building materials and structures – Part 4: Non-combustibility test for materials*

BS 476-20:1987, *Fire tests on building materials and structures – Part 20: Method for determination of the fire resistance of elements of construction (general principles)*

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

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

BS 476-31.1, *Fire tests on building materials and structures – Part 31: Methods for measuring smoke penetration through doorsets and shutter assemblies – Section 31.1: Method of measurement under ambient temperature conditions*

BS 7974, *Application of fire safety engineering principles to the design of buildings – Code of practice*

BS EN 81-58, *Safety rules for the construction and installation of lifts – Part 58: Examination and tests – Landing doors fire resistance test*

BS EN 1363-1, *Fire resistance tests – Part 1: General requirements*

BS EN 1363-2:1999, *Fire resistance tests – Part 2: Alternative and additional procedures*

BS EN 1364, *Fire resistance tests for non-loadbearing elements*

BS EN 1364-1, *Fire resistance tests for non-loadbearing elements – Part 1: Walls*

BS EN 1364-3, *Fire resistance tests for non-loadbearing elements – Part 3: Curtain walling – Full configuration (complete assembly)*

BS EN 1365, *Fire resistance tests for loadbearing elements*

BS EN 1365-2, *Fire resistance tests for loadbearing elements – Part 2: Floors and roofs*

BS EN 1366-1, *Fire resistance tests for service installations – Part 1: Fire resistance tests for service installations – Ducts*

BS EN 1366-2, *Fire resistance tests for service installations – Part 2: Fire dampers*

BS EN 1366-3, *Fire resistance tests for service installations – Part 3: Penetration seals*

BS EN 1366-4, *Fire resistance tests for service installations – Part 4: Linear joint seals*

- BS EN 1366-6, *Fire resistance tests for service installations – Part 6: Raised access and hollow core floors*
- BS EN 1991, *Eurocode 1 – Actions on structures*
- BS EN 1991-1-2:2002, *Eurocode 1 – Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire*
- BS EN 1992-1-2, *Eurocode 2 – Design of concrete structures – Part 1-2: General rules – Structural fire design*
- BS EN 1993-1-2:2005, *Eurocode 3 – Design of steel structures – Part 1-2: General rules – Structural fire design*
- BS EN 1994, *Eurocode 4 – Design of composite steel and concrete structures*
- BS EN 1994-1-2:2005, *Eurocode 4 – Design of composite steel and concrete structures – Part 1-2: General rules – Structural fire design*
- BS EN 1995-1-2, *Eurocode 5 – Design of timber structures – Part 1-2: General – Structural fire design*
- BS EN 1996-1-1:2005, *Eurocode 6 – Design of masonry structures – Part 1-1: General rules for reinforced and unreinforced masonry structures*
- BS EN 1996-1-2, *Eurocode 6 – Design of masonry structures – Part 1-2: General rules – Structural fire design*
- BS EN 1999-1-2, *Eurocode 9 – Design of aluminium structures – Part 1-2: Structural fire design*
- BS EN 10025-1, *Hot rolled products of structural steels – Part 1: General technical delivery conditions*
- BS EN 10025-2, *Hot rolled products of structural steels – Part 2: Technical delivery conditions for non-alloy*
- BS EN 10080, *Steel for the reinforcement of concrete – Weldable reinforcing steel – General*
- BS EN 10147, *Continuously hot-dip zinc coated structural steels strip and sheet – Technical delivery conditions*
- BS EN 10210-1, *Hot finished structural hollow sections of non-alloy and fine grain steels – Part 1: Technical delivery requirements*
- BS EN 10346, *Continuously hot-dip coated steel flat products – Technical delivery conditions*
- BS EN ISO 13943, *Fire safety – Vocabulary*
- BS ISO 10294-1, *Fire-resistance tests – Fire dampers for air distribution systems – Part 1: Test method*
- BS ISO 10294-4, *Fire-resistance tests – Fire dampers for air distribution systems – Part 4: Test of thermal release mechanism*
- BS ISO 10294-5, *Fire-resistance tests. Fire dampers for air distribution systems – Part 5: Intumescent fire dampers*
- BS ISO 10295-1, *Fire tests for building elements and components. Fire testing of service installations – Part 1: Penetration seals*
- BS ISO 22899-1, *Determination of the resistance to jet fires of passive fire protection materials – Part 1: General requirements*
- BS ISO/TR 12470:1998, *Fire resistance tests – Guidance on the application and extension of results*

DD ENV 1187, *Test methods for external fire exposure to roofs*

ISO 834-1, *Fire resistance tests – Elements of building construction – Part 1: General requirements*

ISO 834-4, *Fire-resistance tests – Elements of building construction – Part 4: Specific requirements for loadbearing vertical separating elements*

ISO 834-5, *Fire-resistance tests – Elements of building construction – Part 5: Specific requirements for loadbearing horizontal separating elements*

ISO 834-8, *Fire-resistance tests – Elements of building construction – Part 8: Specific requirements for non-loadbearing vertical separating elements*

ISO 834-9, *Fire-resistance tests – Elements of building construction – Part 9: Specific requirements for non-loadbearing ceiling elements*

ISO 3008, *Fire-resistance tests – Door and shutter assemblies*

ISO 5925-1, *Smoke-control door and shutter assemblies – Part 1: Ambient- and medium-temperature leakage tests*

ISO 10295-2, *Fire tests for building elements and components – Fire testing of service installations – Part 2: Linear joint (gap) seals*

ISO 12468-1, *External exposure of roofs to fire – Part 1: Test method*

ISO/TR 15658, *Fire resistance tests – Guidance for the design and conduct of non-furnace-based large-scale tests and simulation*

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

PD 7974-1, *Application of fire safety engineering principles to the design of buildings – Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)*

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

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

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

PD 7974-6, *The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6)*

PD 7974-7, *Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment*

3 Terms and definitions

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

3.1 calculations (in support of extended application)

calculation methods that can be applied to one or more parameters of a tested construction and which are based on existing physical laws

or have been empirically validated and form part of the process of defining the extended application

3.2 consequence

damage that would occur if the time-equivalent period was exceeded

NOTE With respect to Approved Document B of the Building Regulations for England & Wales [1], consequence is directly proportional to height.

3.3 construction parameter

aspect of the design and construction of an element that may be varied and which can result in a change in the fire resistance performance

NOTE For example, a change in one or more of the dimensions of a stud in a stud framed separating element.

3.4 direct application

variation(s) in the construction and the limits of use for the element which, without further analysis, are covered by the test result in respect to the defined performance characteristics given in Interpretative Document 2 [2] and BS EN 13501-1, achieved from a fire resistance test in accordance with the appropriate European standard

NOTE 1 Direct application is arrived at by the application of simple rules that are known, or considered by the fire community, to give equal or improved fire resistance performance by the users. The rules can be used by non-fire experts.

NOTE 2 Only results from one test report can be used when considering a change of an element. Any combination and use of two or more tests reports or other technical sources is regarded as extended application and dealt with accordingly.

3.5 duration of steady burning

interval between onset of flashover and commencement of decay

3.6 enclosure

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

3.7 expert assessment

engineering analysis carried out by a suitably qualified person so that the results of a fire resistance test can be applied to a building element in which the dimensions and construction detail are different to that tested

3.8 expert judgement

qualitative process carried out by a suitably qualified person when the complexity of the influence is beyond the scope of rules, to establish the resultant effect of a variation in one or more parameters on the classification awarded

3.9 extended application

variations in the construction to establish the limits of use for an element that has been tested in accordance with the appropriate European standard, based upon an analysis by a suitably qualified person

NOTE The extended application can use the results from one or more test reports and can be based upon rules, calculations and expert judgement. As a result of the extended application, the fire resistance classification of an element with respect to defined performance characteristics given in Interpretive Document 2[2] and BS EN 13501-1 can be maintained, increased or decreased when used in practice.

- 3.10 factor**
one of the possible variations that can be applied to a parameter
NOTE For example, a change in the stiffness as a result of a dimensional change in the stud.
- 3.11 factor influence**
potential cause of a change in the fire resistance recorded by test, with respect to one or more criteria when a factor is changed
NOTE For example, an increase in the loadbearing capacity (R) as a result of an increase in stiffness.
- 3.12 fire safety**
safety of a building and its surroundings in relation to life, property, business continuity and the environment
- 3.13 fire safety engineering**
use of engineering principles for the achievement of fire safety
- 3.14 frequency**
measure of the number of fires that are likely to occur in a particular building in a given period
- 3.15 isolated fire**
fire that is fuel-bed controlled and is sufficiently small that it does not directly impact upon the enclosure
- 3.16 probability**
likelihood of failure directly related to cumulative distribution curves of the time-equivalent period
NOTE Probability is derived using a Monte Carlo analysis to evaluate many thousands of fires with all relevant variables that influence fire severity.
- 3.17 protected enclosure**
place of relative safety from the effects of fire
NOTE The effects of fire can include smoke and heat.
- 3.18 risk**
frequency × probability × consequence of failure
- 3.19 rules**
quantitative factors that can be applied to the result of tests when defining the limits of application as a product of research and testing
NOTE Rules are primarily used in determining the direct application of the result, as their application does not require specialist knowledge.
- 3.20 sensitivity analysis**
calculation of changes in outputs for variations of an input parameter of interest
- 3.21 structural frames**
arrangement of structural materials and/or elements coming together to form a building or part thereof designed to fulfil a loadbearing function
- 3.22 structural response**
interaction of loadbearing and non-loadbearing elements or frames as a result of thermal and/or mechanical actions due directly or indirectly to a fire

3.23 thermal and mechanical parameters

aspect of the conditions of a test that can vary in practice and influence the classification system given

NOTE For example, the greater pressure differential that exists at the top of a larger element than the pressure differential at the top of the test specimen.

3.24 time equivalent

duration of exposure to standard BS 476-20:1987, BS EN 1363-1 or ISO 834-1

4 Symbols and abbreviated terms

α	coefficient of thermal expansion (mm/mmK ⁻¹)
α_c	coefficient of heat transfer by convection (W/m ² K)
α_h	area of horizontal openings in the roof related to the floor area of the compartment (m ²)
α_v	area of vertical openings in the façade related to the floor area of the compartment (m ²)
β_0	design charring rate for one dimensional charring (mm/min)
β_n	notional design charring rate (mm/min)
β_{par}	design charring rate under parametric heating conditions (mm/min)
$\gamma_{M,fi}$	partial safety factor in fire
γ_G	partial safety factor for permanent loads to be assigned a value of 1.0
Γ	compartment time factor
Δ_{bow}	lateral deflection of a wall (mm)
Δ_{head}	deflection of head of wall away from the heat source (mm)
ε	strain, emissivity
ζ	reinforcing efficiency parameter of the composite material indicating the extent to which the applied force is transmitted to the reinforcing phase
θ	temperature (°C or K)
λ	thermal conductivity (W/mK)
ρ	density (kg/m ³)
σ	Stefan Boltzman constant (5.67×10^{-8} W/m ² K ⁴)
σ	stress (N/mm ²)
χ_{fi}	reduction factor for flexural buckling in the fire design situation
ψ	partial safety factor
a	effective height (m)
a_0, a_1, a_2	coefficients for thermal conductivity
A	area (m ²)
b	thermal inertia (J/m ² s ^{1/2} K)
ct	combined thickness

C	specific heat capacity (J/kgK)
$d_{\text{char},n}$	depth of charring (mm)
$d_{\text{char},0}$	charring depth for one dimensional charring (mm)
d_{door}	thickness of a door leaf (mm)
d_{ef}	the effective cross section (mm)
d_i	thickness of insulating material, i (m)
d_t	depth of a timber beam (mm)
d_w	thickness of a wall (m)
D	depth of enclosure (m)
$e_{\Delta\theta}$	eccentricity due to variation of temperature across masonry
erfc	complex error function
E	Young's modulus (kN/mm ²)
E	integrity criteria
E	stress-strain slope (kN/mm ²)
$E_{d,t}$	design load created by the fire situation at time t
$E_{fi,d}$	design effect of actions for the fire situation
E_p	plastic modulus (kN/mm ²)
$E_{p,\theta}$	plastic modulus at temperature θ (kN/mm ²)
F	load (kN)
F_t	load at fire temperature
F_0	load at ambient temperature
f	strength (N/mm ²)
F_{e-R}	configuration factor describing the spatial relationship between the emitting and receiving surfaces
h	height (mm or m)
h_{net}	net incident heat flux per unit area (kW/m ²)
H	height of the enclosure (m)
H_p	heated perimeter of a section (m)
I	insulation criteria
I_{mean}	average temperature rise on homogeneous elements
k	thermal conductivity (W/mK)
k	modification factor
k_b	factor describing the thermal properties of the enclosure
k_c	reduction factor
K	thermal diffusivity (m ² /s)
L	linear dimension (mm)
M	moment (Nm)
n	ratio of temperatures
N	design value
$N_{b,fi,t,Rd}$	design buckling resistance
N_{Ed}	design value of the vertical load

O	opening factor ($\text{m}^{1/2}$)
p_c	compressive strength of concrete (N/mm^2)
p_y	characteristic design strength for steel (N/mm^2)
P_w	% of moisture (by mass)
P_f	effective property of the fibres
P_m	effective property of the matrix
q	heat flux (kW/m^2)
q	heat flow (kW)
Q	rate of heat flow (kW)
r	radius
R	mechanical resistance
R	loadbearing capacity criteria
S_{05}	5% fractile of a stiffness property (modulus of elasticity or shear modulus) at ambient temperature
S_{20}	20% fractile of a stiffness property (modulus of elasticity or shear modulus) at ambient temperature
t	time (s, min or h)
T	temperature ($^{\circ}\text{C}$ or K)
V	volume (m^3)
V_i	volume per unit length of an insulated element (m^3)
V_x	matrix volume fraction of a composite
w	width of the opening (m)
w_f	width of the flame front (m); ventilation factor
W	width of enclosure (m)
x	horizontal projection of the flame (m)
x_s	distance from exposed surface (m)
X	flame length along axis (m)
z	vertical projection of the flame above the window (m)
Z	flame height above opening (m)
Z_y	elastic modulus about the minor axis (cm^4)
Z_w	height above the top of the opening (m)

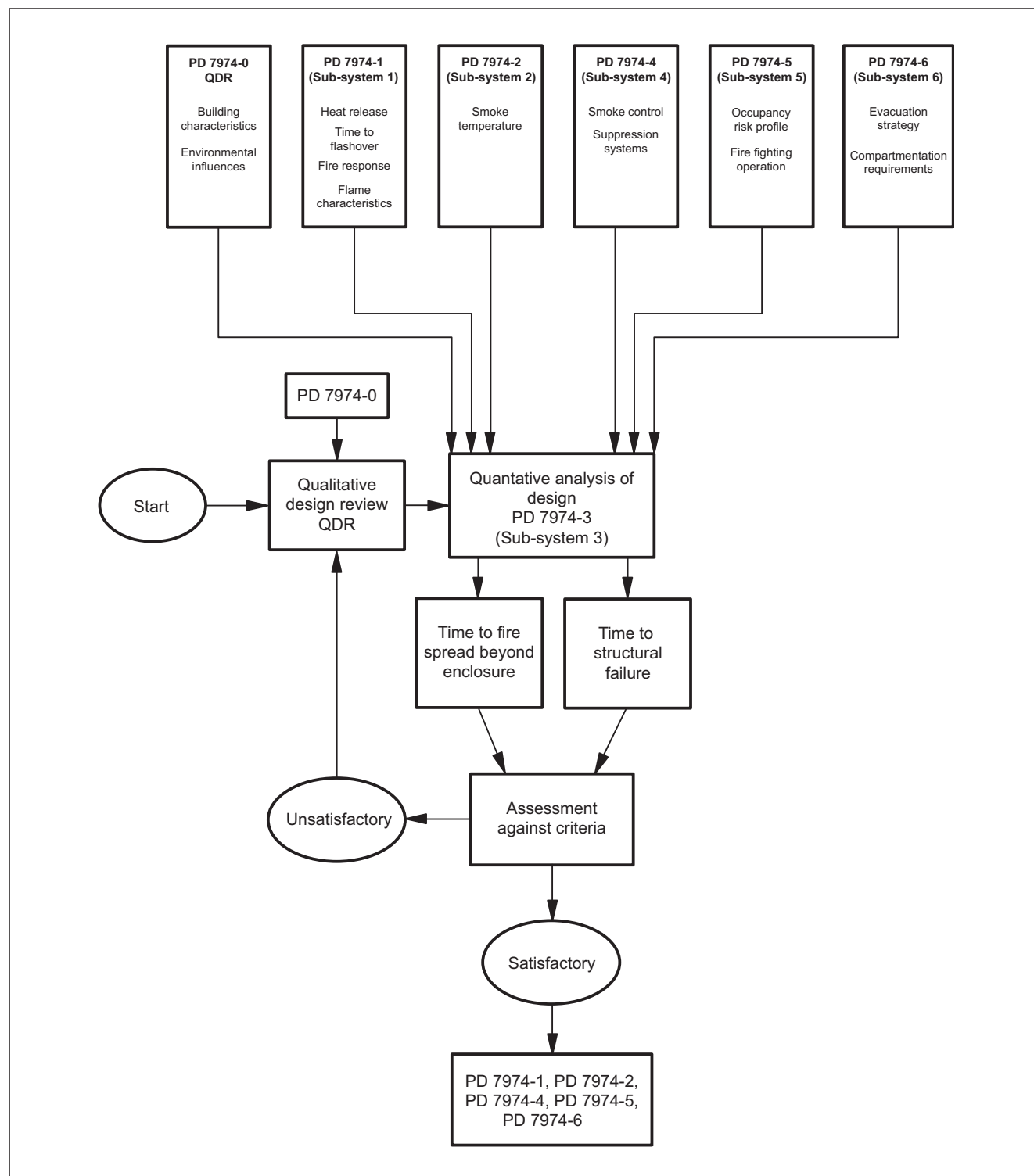
5 Interaction of BS 7974 sub-systems

5.1 General

The BS 7974 sub-systems, or Published Documents, are interrelated and have to be used together in order to achieve a satisfactory solution for the fire safety design of buildings. Decisions made using PD 7974-3 could impact upon other fire safety issues either directly or indirectly and it should not be used in isolation.

The relationships between the inputs to PD 7974-3 and the other sub-systems are shown in Figure 2.

Figure 2 Inter-relationship between PD 7974-3 and the other sub-systems



PD 7974-7 has inputs to all or part of the sub-systems and provides guidance on the application for probabilistic risk assessment for fire safety engineering in buildings.

5.2 Inputs into PD 7974-3

5.2.1 PD 7974-0: Building characteristics and environmental influences

5.2.1.1 General

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

5.2.1.2 Enclosure layouts and geometries

The layout and geometry of an enclosure influences the thermal conditions expected during a fire and the mechanical response of the enclosure to such conditions. The dominant variables include W , D , A_f , A_t , A_w , A_T , h_w and w (see Clause 4).

The identification of ventilation openings and potential routes for fire spread should take into consideration the issues discussed in Clause 8.

5.2.1.3 Construction details

It is important to understand the constructional form of the enclosure and to identify any load paths that could 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 need to be understood in the context of evaluating the expected fire conditions.

The key parameters include λ , ρ and C (see Clause 4).

Annex A gives some data illustrating the order of these properties for some typical construction materials. These properties 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 could provide a reasonable approximation.

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 could result in exothermic or endothermic reactions.

5.2.1.4 Structural loads acting

It might be necessary to identify the nature and magnitude of the loads as actions imposed on the structural members within the enclosure. These loads could include self-weight, permanent dead loads and various live loads. Guidance on the combination of loads is given in Clause 12.

5.2.1.5 Fire load

The quantity of combustible material, both within the enclosure and forming part of the building fabric, influences the conditions that exist during a fire. PD 7974-1 examines how to establish the quantity of fire load present and includes tables that describe typical fire load densities for different occupancies and calorific values of building materials.

5.2.1.6 Characterization of adjacent enclosures, spaces and buildings

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 via openings etc., ignite combustible items in the adjacent enclosures. The designer might 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). If the analysis described in PD 7974-3 indicates that ignition of items occurs in an adjacent enclosure, subsequent determination of fire growth and development in the adjacent enclosure should be undertaken in accordance with PD 7974-1.

5.2.1.7 Environmental influences

The climatic conditions external to the enclosure of fire origin can influence the nature of the flames issuing from openings (see Clause 9). It might therefore be necessary to take account of the prevailing wind direction and design velocity (m/s). Snow loads or seismic loads might need to be considered when determining the mechanical response of elements of structure.

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

PD 7974-1 provides information relating to the fire (see Clause 9) and includes:

- rate of heat release during the post ignition/combustion phase;
- time to flashover;
- temperature-time response of the fire;
- characteristics of the flames, e.g. size: length and thickness, temperature, radiation, emissivity.

Although the period leading up to flashover impacts upon the enclosure, the most important part of the fire is the interval between the onset of flashover and the commencement of decay, known as steady state burning. It is during this period that the capacity of the enclosure to contain fire and the maintenance of structural function is most challenged. 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.

5.2.3 PD 7974-2: Spread of smoke and toxic gases within and beyond the enclosure of origin

The smoke temperature determines the rate of heat transfer through fire enclosures that have little or no insulation. In atria for example, entrained air determines the smoke plume characteristics, buoyancy and temperatures on the exposed side of glazing.

PD 7974-2 also provides information on excess pyrolyzates.

5.2.4 PD 7974-4: Detection, activation and control

The time at which smoke control and fire barriers operate influences the temperature rise within the enclosure. Activation of the smoke control removes hot gases and reduces the heat transfer to structural members and enclosures. Reduction in smoke volume maintains integrity of even non-fire-rated enclosures.

The activation of fire barriers, door/shutter release and damper systems contain the fire, potentially increasing enclosure temperatures. Activation of shutters separating compartments or buildings reduces heat transfer by radiation and fire spread.

The activation of suppression systems limits the size of the fire and potential enclosure temperatures and reduces fire spread to adjacent buildings, either from flying brands or radiation. Suppression systems keep the temperature of structural components below their critical temperature, thereby preventing significant distortion or collapse. Enclosures that are not fire resistant in terms of standard furnace testing might withstand a moderate rise in temperature without loss of "notional" stability or integrity or heat transfer to the adjacent enclosure.

5.2.5 PD 7974-5: Fire service intervention

The time at which the fire service intervenes affects the structural behaviour and fire spread beyond both compartments and non-fire-rated enclosures. The type of building, e.g. single or multi storey, and the occupancy profile or risk profile influences fire-fighting operations and the need for containment.

5.2.6 PD 7974-6: Human factors – life safety

The fire safety strategy for the evacuation of the occupants determines the fire resistance requirements for the structure and compartment. Evacuation can be phased or simultaneous, with the former requiring a greater assurance on the stability and integrity of the structure.

In some types of occupancy, such as residential buildings, the normal approach to fire safety is to evacuate only the occupants directly affected by the fire. The remainder stay within their apartment, relying upon adequate compartmentalization to maintain their safety. In other cases, where the occupants could have impaired mobility and either require assistance or cannot be evacuated, refuges might be required in which a greater degree of compartmentalization would be necessary.

5.2.7 PD 7974-7: Probabilistic risk assessment

PD 7974-7 should be reviewed during the design process and provides deterministic calculations. Input data and analytical methods in PD 7974-7 should be considered in terms of their reliability, confidence in their representation (characteristic design values) and their limits of applicability.

5.3 Outputs from PD 7974-3

5.3.1 Building characteristics

Analysis undertaken in accordance with this Published Document might conclude that changes to the enclosure boundaries, e.g. failure of surfaces, opening of gaps or alteration to the structural form

such as deflection or collapse of loadbearing elements of structure, could occur. These changes in the characteristics of the building need evaluating in their own right as part of the qualitative design review (QDR) process. The variable boundary conditions should also be considered when analysing adjacent enclosures within the building.

5.3.2 Time to fire spread from enclosure

The QDR establishes what constitutes spread of fire from the enclosure of origin. The analysis described in this Published Document determines the time at which ignition of a fire occurs in a space or enclosure outside the enclosure of origin. In addition, guidance is given on how to determine the conditions generated outside the enclosure by a fire inside the enclosure, e.g. the extent of heat radiated from openings. These conditions (and their changes over time) might need evaluating in their own right as part of the QDR where they could affect other fire safety issues, e.g. the movement of persons within the building.

5.3.3 Time to structural failure

The QDR establishes what constitutes failure of the structure. 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 saving the lives of the building's occupants, a larger degree of structural movement can be accommodated than, for example, in designs where the objectives relate to observing a maximum level of damage and financial loss. For example, research by Corus (Tata Steel) at the Swinden Technology Centre and the Building Research Establishment (BRE) [3] has shown that continuous building frameworks are potentially capable of maintaining stability despite the loss of strength of individual beams or columns. The QDR should consider whether local buckling of a column, or the loss in loadbearing capacity of a floor beam with associated deflections of the floor slab, constitutes failure in a building which remains otherwise stable. The designer should be aware of disproportionate collapse issues. The time to structural failure can only be quantified if failure has been adequately defined within the QDR. The same issues arise in concrete structures and other constructional materials where continuity of load paths is attributed to members outside the immediate fire zone.

5.3.4 Risk assessment

The outputs should also be considered in terms of consequences of failure as defined in the QDR, whether it is failure of an enclosure or compartment, fire spread or loss in structural stability.

6 Design approach to PD 7974-3

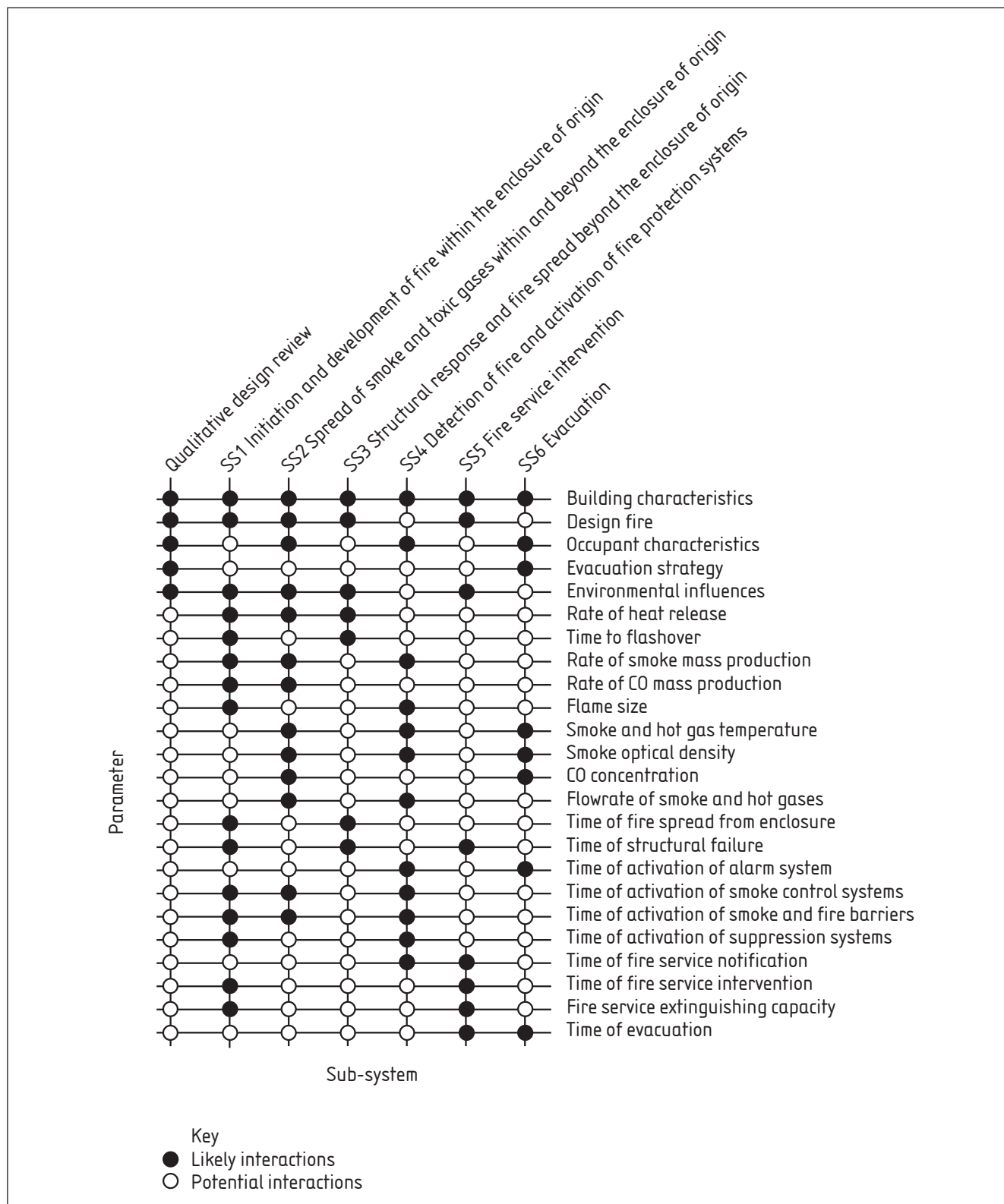
6.1 General

A framework for the application of engineering approaches to fire safety in buildings is provided in BS 7974.

PD 7974-0 assists with the design process. The quantitative design analysis is divided into a number of separate sub-systems. Each

sub-system can be used in isolation when analysing a particular aspect of design, or can be used in combination as part of an overall fire evaluation of a building. Figure 3 illustrates potential interactions between the sub-systems. The parameters are often inputs into one sub-system and outputs from another.

Figure 3 Methodology for interaction of all sub-systems in the PD 7974 series



Each of the sub-systems concentrates on the quantified analysis state of the BS 7974 framework, however additional guidance (specific to the relevant sub-system) is useful when considering the overall framework. This subclause provides guidance on the interaction between PD 7974-3 and the overall BS 7974 framework, and defines the process for quantitative analysis of the structural response and the likelihood of fire spread beyond the room of fire origin.

6.2 Interaction with BS 7974 framework

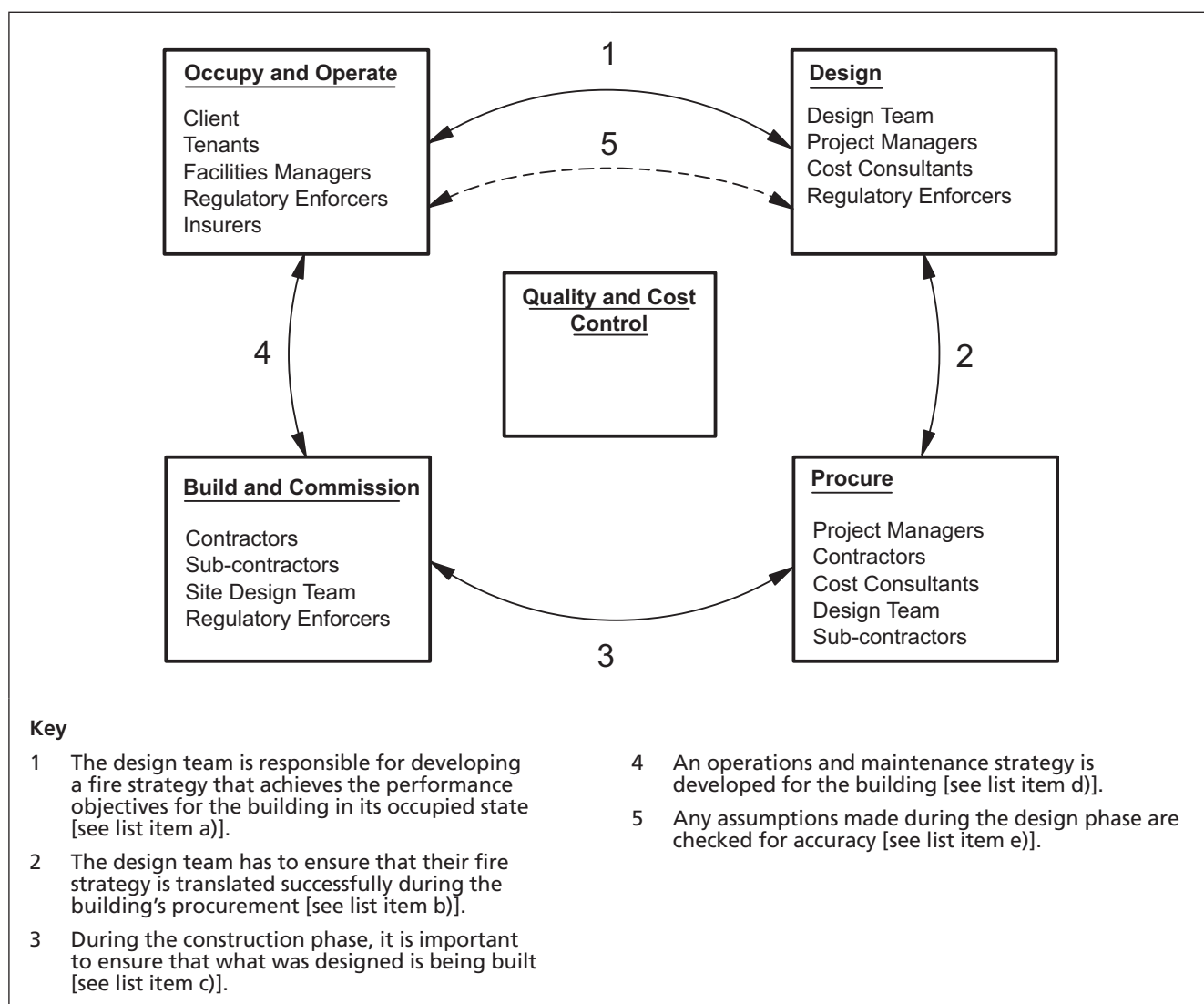
The BS 7974 framework is shown in Figure 1. The preliminary part of the framework is to conduct a QDR comprising several components, defined in BS 7974, during which the relevant sub-systems should be considered. Clause 6 provides guidance on how PD7974-3 interacts with the various components of the QDR and some of the issues to be considered within the QDR.

6.3 Personnel involved in the QDR

Input from all critical members of the design team is required for a successful PD 7974-3 analysis. The relevant parties and their level of involvement depends on their role in achieving the objective(s) of the analysis. To determine the relevant parties, it is worth considering the development of a building from concept to occupation. Figure 4 is a schematic representation of the circle of fire safety during the design and construction of a building. The key and the following list show the steps that are involved in delivering a successful fire strategy and use the example of fire load assumptions to demonstrate the process.

- a) During the design phase, certain assumptions are made about the building occupancy, potential risks and how the building is managed and operated, e.g. a fire load is assumed for certain areas of the building. In some areas, sprinklers might be required to ensure fire sizes are controlled.
- b) The design team use the tender documentation, which is likely to include the fire strategy and appropriate performance specifications to ensure that the fire strategy is translated successfully. The tender specification should outline the areas to be covered by the sprinklers and the performance requirements of the sprinklers.
- c) If there are onsite changes, these should not impact on the fire strategy and, if they do, the fire strategy should be altered to accommodate the changes. For example, the correct sprinkler systems should be installed in the correct areas.
- d) The operations and maintenance strategy should ensure that fire loads are controlled where necessary and an appropriate maintenance procedure should be in place for the sprinkler system.
- e) If changes are made, these should not compromise the fire strategy. The fire strategy should be revised to ensure that the objectives are achieved for the as-built and occupied condition. For example, if the occupancy is more hazardous than originally envisaged and the desired objective cannot be achieved, remedial measures should be put in place.

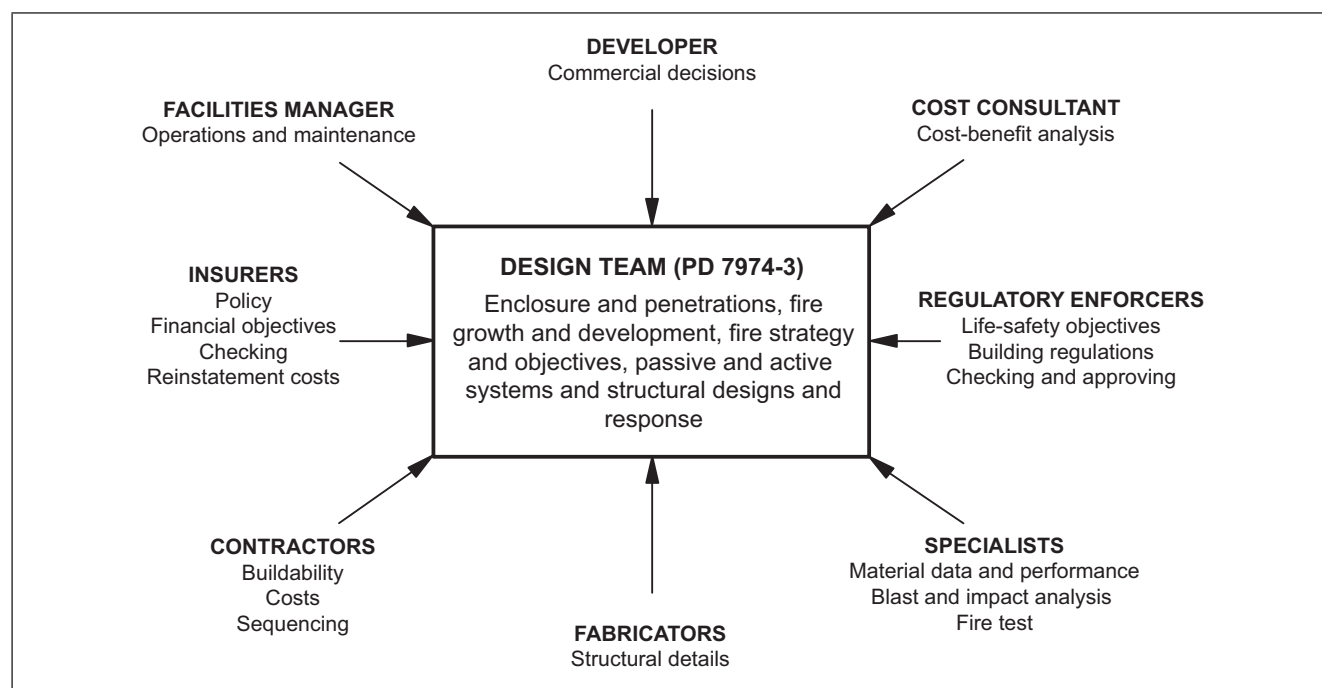
Figure 4 Interaction between the various professionals as part of the process in delivering a successful fire strategy



Throughout the process, quality and cost should be managed and controlled.

Having looked at the key components of the building process, it is possible to identify the parties that might be involved in PD 7974-3, listed in Figure 5. Not all parties need to be involved, and those who are do not have to be involved throughout the whole process. This is not an exhaustive list and the person responsible for conducting the PD 7974-3 study should ensure all relevant parties are involved at the appropriate time. The personnel involved in the QDR can vary throughout the process.

Figure 5 Interaction between the various professions and the design team in addressing PD 7974-3 factors



6.4 Experience and qualifications

The complexity of the interactions between people, buildings and fire varies such that no single set of calculations can be applied to all buildings in all circumstances. Therefore, fire safety engineering (FSE) requires a greater degree of care and responsibility by the designer than the application of prescriptive codes. The application of FSE should be entrusted to suitably qualified (in the appropriate field) and experienced personnel. Engineering Council-recognized corporate engineers from a fire or related construction-based discipline can be considered suitably qualified.

6.5 Timing of QDR

The QDR should be carried out early in the design process so that any substantial findings can be incorporated into the design of the building before the architectural drawings are developed. However, in practice, the QDR is likely to involve some repetition as the design process moves from broad concept to detailed design.

6.6 Establish fire performance objectives

The fire safety objectives can be applied to the fire strategy as a whole (for example the structure should maintain its stability for a sufficient period to allow the safe evacuation of all occupants), or it can be more specific (for example the design of a compartment wall, including any penetrations or openings, should conform to BS 476-20).

The fire safety objectives should take account of one or more of the following: life safety [see a)], property protection and business continuity [see b)] or environmental protection [see c)].

- a) Life safety objectives typically consider overall building stability, maintaining the tenability of escape routes, fire containment, prevention of external fire spread, and/or protection of fire fighters.
- b) Property protection and business continuity objectives typically consider damage limitation, fire and smoke containment, and/or reinstatement costs and time.
- c) Environmental objectives typically consider fire, smoke and run-off water containment.

6.7 Identification of fire hazards and possible consequences

6.7.1 General

In the context of PD 7974-3, the primary hazards and possible consequences derive from structural failure and/or fire spread beyond the enclosure of fire origin. Therefore, as part of the QDR, it is necessary to understand the mechanisms of fire spread (see Clause 7) and potential routes for fire spread (see 6.7.4).

6.7.2 Mechanisms for fire spread

6.7.2.1 General

Assuming that fire starts within an enclosure, it 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.

6.7.2.2 Conduction

The solid boundaries of an enclosure have one surface exposed to fire conditions whilst the other, non-exposed surface faces 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 the fire spreading to adjacent spaces, known as insulation failure of the enclosure. Heat can be transmitted by direct conduction to the non-exposed side of boundary elements or, by indirect conduction, through building components that are continuous on the outside of the enclosure, e.g. pipes, ducts, beams and columns.

Whether the heat conducted to the non-exposed surface causes the spread of fire depends upon the effect this heat has on adjacent

spaces. The heat conducted to the non-exposed surface from the fire enclosure can precipitate fire spread through:

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

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

6.7.2.3 Convection

The flow of hot gases or flames through openings, whether fixed or a result of integrity failure in the enclosure, can cause ignition of combustible items in adjacent spaces. In addition, collapse of the boundary element, due to, e.g. its failure to remain sufficiently loadbearing under fire conditions, can also permit transmission of fire through excessive convection. Heat flow through openings is difficult to quantify, particularly in the stage between initial integrity failure and total collapse.

6.7.2.4 Radiation

The transmission of heat from openings in the enclosure can 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.

6.7.2.5 Mass transfer

Burning fuel items within the enclosure can be transferred to other enclosures through fixed or fire created openings as a result of integrity failure. Examples include the projection of flying brands and the flowing of liquid pool fires under doors with no bund protection.

6.7.2.6 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, for example with lateral fire spread within the thickness of combustible walls and roofs. Successful fire stopping of pyrolysis routes is influenced by the characteristics of the flammable materials present and the mechanical stability of the overall system. For example, continuous members extending beyond the enclosure could permit fire spread by pyrolysis via a continuous combustible component. Fire stopping can 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.

6.7.3 Factors influencing fire spread

The likelihood of fire spreading beyond its enclosure can be influenced by:

- the fire resistance of the boundaries on the enclosure, e.g. 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, determined by the amount of fire load and ventilation present;
- measures to reduce the severity of a fire by reducing its capacity to penetrate enclosure boundaries, e.g. the installation of an automatic sprinkler system (direct) or by limiting the ventilation available to the fire or limiting the amount of combustibles available to fuel it (indirect);
- the size of the enclosure, e.g. fires in atria or single storey premises with high roofs 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 which can increase fire severity through introduction of ventilation and through draughts, and vertical routes which can permit fire spread in the absence of appropriate fire dampers;
- the presence of concealed spaces (e.g. above false ceilings, within hollow construction and under floors), which can increase the potential for fire to spread undetected;
- the air pressure conditions within the enclosure and pressure differentials between enclosures, which can reduce fire spread by the release of heat through ventilation. 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, e.g. loss of air-tightness through poor workmanship in construction, unstopped joints and service penetrations can provide easy routes for fire spread;
- the deformation of structural elements can open gaps in an enclosure's boundaries in a gradual or sudden manner, e.g. through application of load to non-loadbearing assemblies;
- voids behind curtain walling systems, e.g. systems incorporating 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.

6.7.4 Routes for fire spread

Once the enclosure has been characterized, the designer should identify all possible routes of fire transmission through the boundary surfaces. Figure 6 illustrates some of the more common direct routes for potential fire spread. In many instances, the designer should also consider the potential for fire spread between two adjoining enclosures via independent spaces. These routes of fire spread should be examined as a series of direct spread mechanisms.

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

Figure 6 Routes for fire transmission

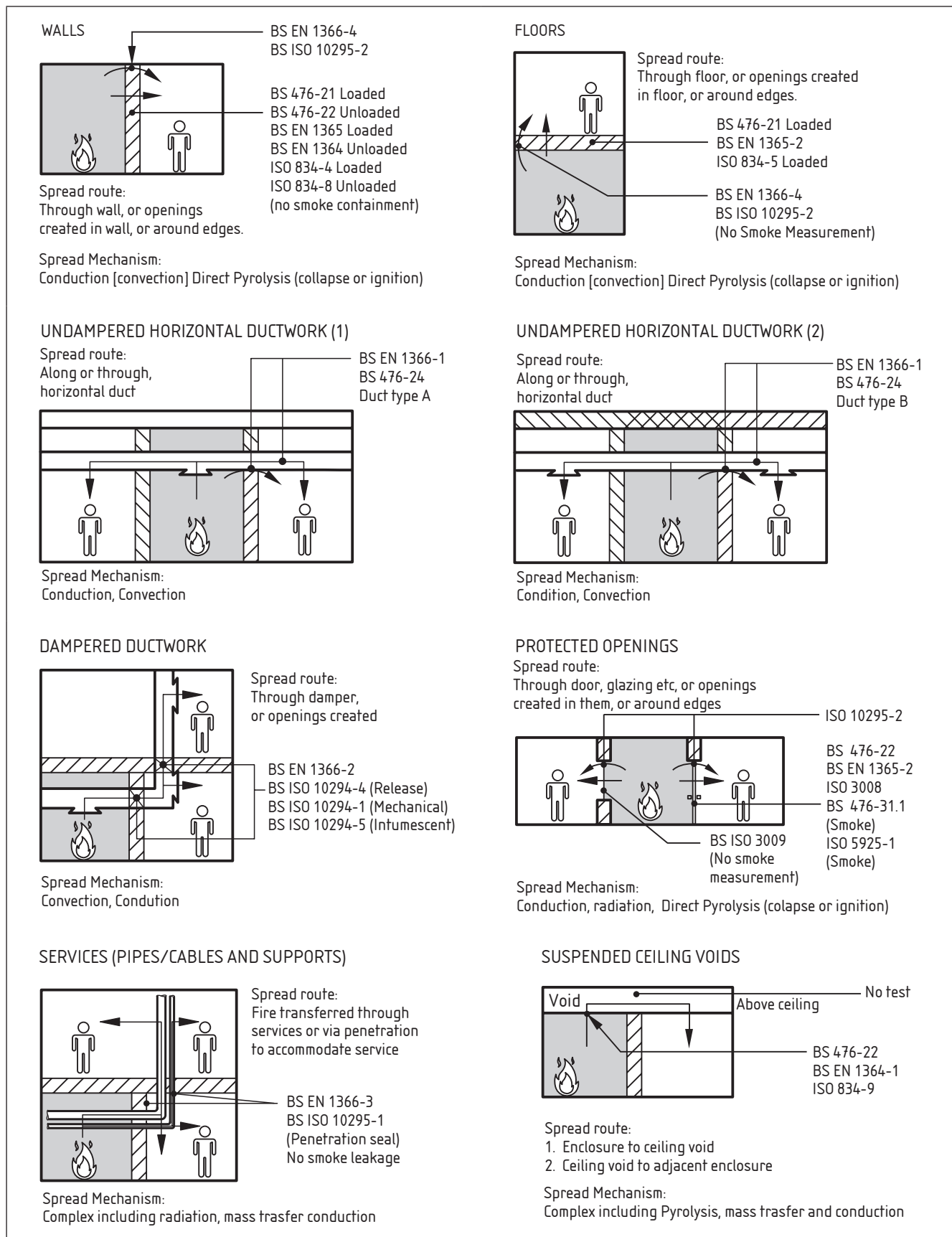
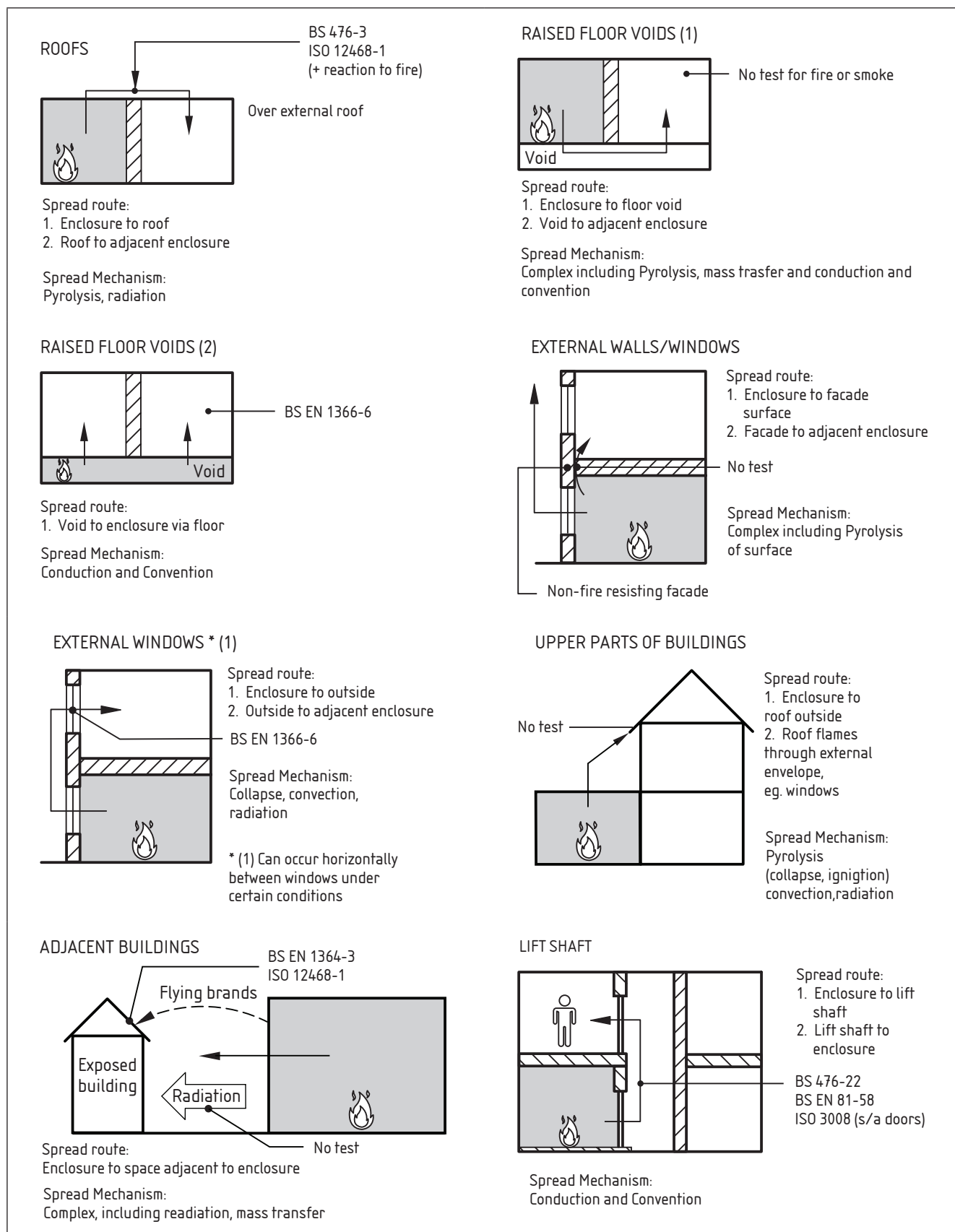


Figure 6 Routes for fire transmission (continued)



6.8 Establishing trial fire safety designs

6.8.1 General

Having identified and evaluated the potential hazards and their consequences, the designer should mitigate the hazards, and/or demonstrate that the consequences of the hazards are acceptable. The trial design is the designer's initial attempt at developing a solution likely to meet the desired fire safety objective, which is then tested through quantitative analysis. Typically, for PD 7974-3, the trial design should consider:

- fire resistance of the structure including any applied fire protection;
- extent, frequency and performance of fire barriers;
- influence of any suppression measures;
- effectiveness of, or need for heat and smoke extract;
- fire service intervention and effectiveness.

The trial design should also consider the level of redundancy, robustness and reliability that is acceptable, and specifications should be produced to ensure these.

6.8.2 Redundancy

Redundancy or diversity ensures that an alternative is available if a particular feature or system becomes compromised. For example, providing alternative structural load paths or not taking into account the beneficial effects of sprinklers in the analysis constitutes a level of redundancy.

6.8.3 Robustness

The robustness of the system is its ability to perform its function, even if the exposure conditions are not exactly as predicted and the condition of the element at the time of the event is worse than anticipated. Robustness is more important where redundancy is not possible.

6.8.4 Reliability

Reliable systems are those likely to perform as required. Reliability can be improved through the use of reliable components, where their quality and installation are accredited by a third party and these are subjected to appropriate maintenance and testing.

6.9 Identification of acceptance criteria and appropriate methods of analysis

6.9.1 General

The acceptance criteria, as defined in the QDR, should be applicable to the fire safety objective (see 6.6) and can be deterministic or risk-based (where risk is the potential consequence of an undesirable event). Typically, the acceptance criteria are expressed in terms of loadbearing capacity, integrity and/or insulation. The acceptance criteria can use predetermined levels of acceptance, such as the criteria specified in BS EN 1363-1 and BS EN 1363-2, or they can be derived to mitigate the identified hazard.

6.9.2 Factors influencing life safety acceptance criteria

The life safety of people in or around the building, including fire-fighters and search and rescue, is compromised if the structure collapses with people inside or within range of the building. Similarly, life safety is threatened if the tenability of the space people are in, or need to pass through to exit safely, is outside the limits they can withstand, taking into account any personal protection they might have, such as breathing apparatus.

Factors to consider when assessing the ability of the building to withstand collapse for the requisite period are usually derived from the required safe egress time analysis (see PD 7974-7) and include:

- loss of loadbearing capacity of structural members;
- rate of deflection; and
- the maximum permissible stress or strain.

The following factors need to be considered when analysing the security of relevant spaces:

- integrity and smoke tightness of the elements forming the structure in respect of the leakage of fire and gaseous combustion products into protected enclosures;

NOTE 1 This is usually the product of collapse of boundary elements, deflection or distortion, propagation of cracks and fissures, or the burning through or melting out of component parts.

- insulation and radiation of the elements forming the structure in respect of ambient temperature within the exit routes and protected enclosures.

NOTE 2 This is usually the product of tightness but, prior to any loss of smoke tightness and/or integrity, it is influenced by the conducted/convective and radiant heat emitted by the fire separating elements of structure.

The standard criteria used in the fire resistance tests, as appropriate to the element being tested, might have little or no direct relationship to the critical tenability levels. However, there is probably a fairly high level of redundancy in the solution derived if they are used.

NOTE 3 A more detailed consideration of the applicability of the conventional criteria can be found in ISO/TR 22898.

6.9.3 Factors influencing property protection and business continuity acceptance criteria

The criteria for property protection and business continuity are likely to differ from those for life safety. Instead of calculating a time to failure, it is more likely that PD 7974-3 would be used to assess the level of potential damage that occurs for different fire scenarios and determine whether this is acceptable in terms of:

- value of capital losses;
- loss of income; and
- extent of damage and reinstatement costs.

The method of quantifying the acceptability of the enclosure's fire behaviour with respect to the property protection and business continuity is not dissimilar to methods for life safety (see 6.9.2), except the critical conditions relate to the ability of the structure, equipment,

processes and products to withstand the conditions predicted to prevail in the spaces during fire.

If the analysis shows that the enclosure, equipment, processes and products cannot withstand the conditions predicted by the analysis, the conditions should be mitigated by the provision of enhanced integrity and insulation levels from the separating elements.

6.9.4 Factors influencing environmental acceptance criteria

The impact of fires on the environment can be considerable, particularly in buildings that house industrial or chemical processes or storage. In such situations, preventing fire spread can significantly reduce the risk of contamination and the following acceptance criteria are usually considered:

- the ability of the structure to contain the products of combustion and load and prevent fire spread into environmentally sensitive areas;

NOTE The performance levels used can differ from those used for life safety, or even property protection, particularly the insulation criteria which reflect the nature of the contents of the risk area.

- the maximum allowable quantity of combustion gases released;
- the area of damage (direct and indirect);
- energy released by fire;
- energy and resources consumed in controlling fire.

6.10 Establish fire scenarios for analysis

BS 7974 provides considerable advice on the selection of fire scenarios. With PD 7974-3, the following should be considered.

- In order for fire or smoke to spread beyond the enclosure of origin it is often assumed that a post-flashover fire occurs, which is not necessarily true.
- When assessing the performance of structural elements it is often assumed that a fully developed compartment fire represents the worst case. This is usually true but a localized fire sometimes represents the worst case, for example in structures that are susceptible to restrained thermal expansion.
- It is often assumed that all elements being heated simultaneously represents the worst case, which is not necessarily true.
- Failure can often occur in the decay phase of a fire so it might be necessary to include decay in the analysis.
- The behaviour of real fires is very sensitive to the amount of ventilation available. Well-vented fires tend to be short-lived, the converse being true for under-ventilated fires. The performance of structural and separating elements is sensitive to the combustion temperature and duration of fire exposure and the hottest or the longest fires do not necessarily represent the worst case. Therefore, the number and range of design fires should be carefully considered to ensure a reasonable range of conditions is evaluated.

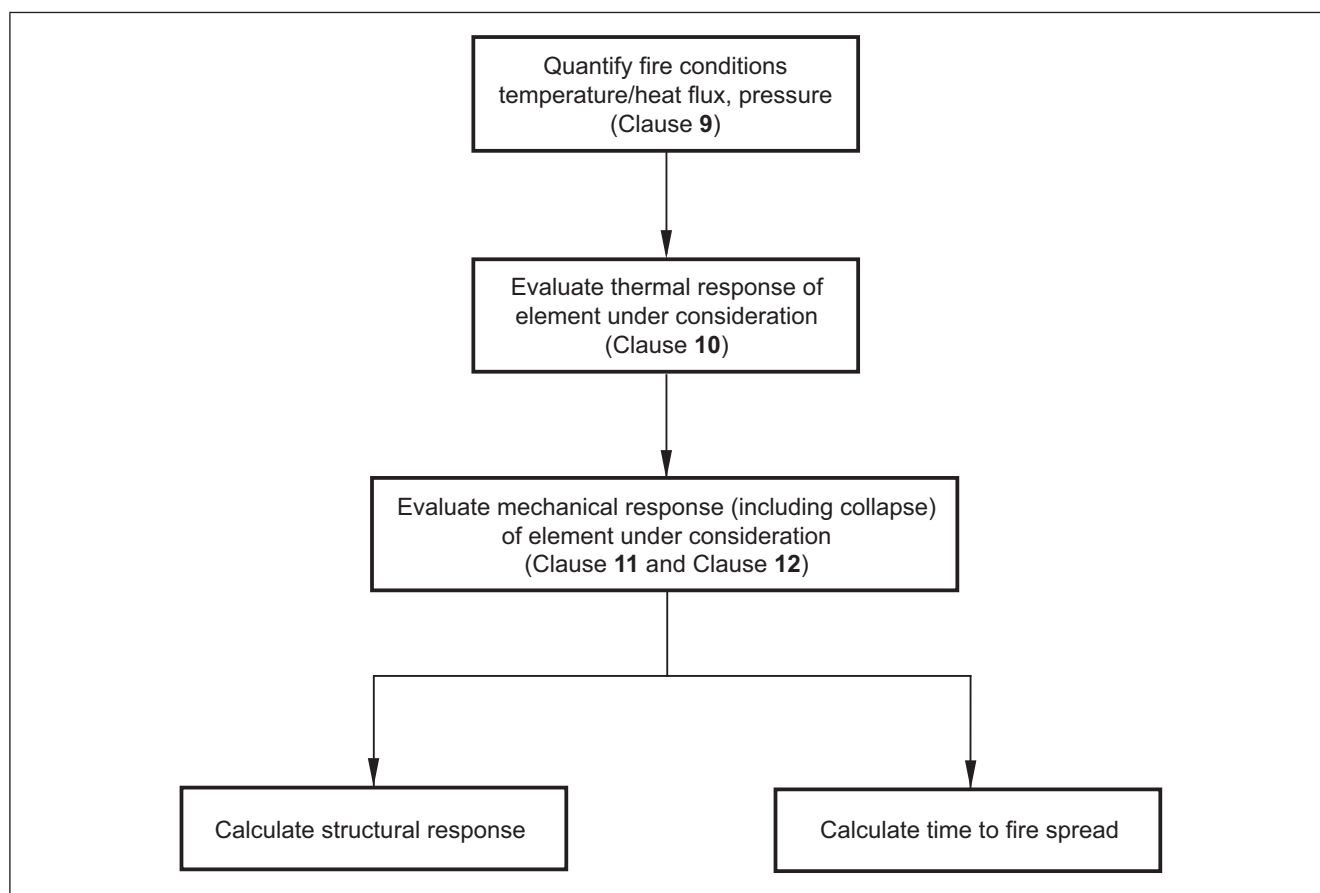
6.11 Quantitative analysis

6.11.1 General

The primary focus of each of the BS 7974 sub-systems is the quantitative analysis, and the results of the analysis should be supplied by the sub-systems as output to the assessment stage of the BS 7974 framework. The process should be completed for each of the fire scenarios and each of the potential routes of fire spread identified within the QDR.

The process for quantitative analysis that should be conducted as part of PD 7974-3 is defined in Figure 7. Each step can be conducted sequentially or combinations of the steps can be conducted simultaneously.

Figure 7 Procedure for quantitative analysis within PD 7974-3



6.11.2 Defining analysis methods

The science behind each of the parts of the quantified analysis of PD 7974-3 is complex and there are several methods. These include prescriptive guidance, testing, empirical relations, expert judgement and varying complexities of quantified analysis. Each method has its own associated accuracy and range of applicability. It is up to the designer to select the appropriate method for the problem in hand, and this is a function of the objectives, the potential hazards and consequences, the required accuracy and the required output.

6.11.3 Defining the fire enclosure and its openings

6.11.3.1 General

The fire conditions are directly influenced by the size, geometry and construction of the enclosure of origin. Therefore, it is important to accurately define the enclosure prior to conducting the analysis and to redefine it during the fire exposure, as the enclosure boundaries can change as a result of the changing conditions. Guidance on the characterization of the boundary is given in Clause 8.

6.11.3.2 Characterizing the boundary of the fire enclosure

All nominally impermeable boundaries in a building inhibit the spread of fire. Certain boundaries are purpose-designed to prevent fire spread and are generally designed against codes of practice which incorporate elevated temperature of fire case data. When these do not exist, the boundaries are assessed by fire engineers with the relevant knowledge of the high temperature response of various forms of structure and/or materials, or are tested in a standard furnace to assure their fire-resisting performance. The fire safety strategy established in the QDR designates those boundaries required to resist fire spread and the duration for which they are required to do so. Even non-fire-resisting elements forming an enclosure influence the rate of growth of the fire. The ongoing capability of these initial enclosing surfaces to remain impermeable to the spread of fire is a function of their construction and the fire condition, which can be subject to change. Accordingly, the nature of the fire enclosure should be viewed as time-dependent, requiring ongoing analysis.

6.11.3.3 Characterization of fixed openings (doors, windows, vents etc.)

The fire conditions within an enclosure are influenced by the size, shape and extent of openings which permit airflow into the fire and the outflow of heat and combustion products from the enclosure. Where a combination of fixed opening conditions is a possibility for the fire enclosure, e.g. some doors open, some doors closed, options which are most conducive to fire spread (a worst case scenario) should be considered. However, the use of worst case scenarios might not be valid if good management of openings forms part of the strategy. In the case of doors, the use of closing devices without damping, or with high closing forces, can lead to the doors being wedged open. Such a practice lessens the effectiveness of the enclosure, both for containing fire and restricting oxygen availability. Abuse of the door can be prevented by the use of:

- electromagnetic hold-open devices;
- delayed closing face fixed overhead closers; and
- swing free closers.

The use of compatible hardware, such as hinges and latches increases the probability of the door being closed.

Keeping doors closed during a fire is also dependent upon a number of features, such as the type and dimensions of door edge sealing systems, and their ability to remain closed against normal fire pressure fluctuations and differential distortions between leaf and frame.

Similarly, dampers in air transfer systems that are electrically operated by an actuator linked to the detection system are more reliable than

dampers that are operated by a thermal link. Penetration of the enclosure boundary by services (plastic and metal pipes and cables) is less likely to cause the enclosure to lose integrity if the sealing system can compensate for the erosion of the associated construction.

Glasses used for glazed openings are more reliable if they maintain integrity when subjected to changing temperatures.

The specification and design of sealed openings is a much neglected aspect of fire containment and expert guidance should be sought if the enclosure boundaries are critical to the performance. Any modelling of the enclosure fire dynamics, especially Computational Fire Dynamics (CFD), requires an understanding of the reliability of the enclosure to make accurate predictions. Control over the boundary is therefore critical, and it is only by attention to such details that reliability can be achieved.

6.11.4 Defining fire conditions

To predict the structural behaviour of individual elements of the enclosure, or quantify the integrity, smoke tightness and insulation characteristics of the fire separating elements of the enclosure, it is critical to have detailed information on the fire conditions to which they are exposed. The fire conditions change the longer the fire continues. As the fire grows, the amount of fuel involved increases though a shortfall in the air (oxygen) supply and the intervention of any automatic suppression system can delay this trend. The thermal response of the boundary and the structural elements can only be predicted with accuracy when the fire conditions, with respect to time, have been accurately quantified (see Clause 9).

It is not only the temperature within the enclosure that is important. Any pressure differential between the inside of the enclosure and the adjacent areas has a significant influence on the rate at which the tenability of the protected spaces is lost. In any natural enclosure fire there is generally a gas pressure generated above a certain height, normally referred to as the neutral axis. Above the neutral axis there is a stimulus for convection (see 6.7.2.3), whereas below the neutral axis the stimulus is very low or non-existent. In some fire strategies depressurization is used to reduce the spread of fire through openings where the provision of a robust seal is difficult. The standard fire resistance test incorporates a neutral axis and a positive pressure differential, but this is not always the case in practice, making the application of the results of standard fire tests problematic, for example with the risk of fire breaking into a building. Prevailing wind conditions could require greater provision in some situations.

When defining the fire conditions, it is therefore important to consider both the temperature and pressure conditions.

Whilst unquantifiable, turbulence in the fire could make the results of some fire tests inappropriate if the construction materials are not robust enough to withstand this.

6.11.5 Heat transfer and thermal response

Heat is transferred from the fire into elements of the structure by means of conduction, convection and radiation. Heat transfer assessments determine the amount of heat being transferred into the structure via its surfaces.

Having established the amount of heat that is transferred into the structure via its surfaces, the next stage is to determine how the heat is transferred throughout the element. The heat transfer and thermal response calculations are often conducted simultaneously (see Clause 10).

6.11.6 Structural response

6.11.6.1 General

As an enclosure or separating element changes temperature, its structural response changes as a result of corresponding changes in material properties. The purpose of the quantitative analysis is to determine structural response as a result of the thermal response. The purpose can vary depending on the reason for conducting the analyses and can reflect life safety, property protection, business continuity and/or environmental protection objectives.

6.11.6.2 Changes in building characteristics

Analysis undertaken in accordance with this Published Document could identify changes to the enclosure boundaries such as failure of surfaces, opening of gaps, or alteration to the structural form, e.g. deflection or collapse of loadbearing elements of structure. These changes in the characteristics of the building should be evaluated in their own right as part of the QDR process as they can compromise the fire strategy objectives. The changes might also need to be considered as variable boundary conditions when analysing adjacent enclosures within the building.

6.11.6.3 Time to fire spread from enclosure

The time to fire spread from the enclosure of origin is discussed in 5.3.2.

6.11.6.4 Time to structural failure

The time to structural failure is discussed in 5.3.3.

7 Analysis of mechanisms of fire spread

7.1 Forms of analysis

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

The behaviour of any individual element can be determined by:

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

Certain mechanisms are best analysed through practical tests, whilst others can be analysed using 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 increases the design efficiency.

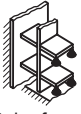
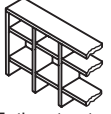
Table 1 indicates the possible combinations of fire and structural analysis. It is possible that alternative combinations are justifiable. Equally, some of the combinations might not be valid and the designer should justify his decision.

NOTE For potential outputs that can be obtained from various analysis methods, see Figure 8.

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

Mechanism	Standard test	Experimental tests	Expert assessment	Engineering calculations
Conduction	BS 476-20 (Insulation criteria) (See 7.2.5)	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 (Insulation criteria) (See 7.2.5)	Ad hoc fire tests possible	Suited to expert assessment from the results of fire tests	If openings are known, the convection of hot gases can 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 1363-2 (Radiation measurements)	Standard experiments and ad hoc fire tests possible	Generally requires full calculation	If openings are known, a range of well-established and verified radiation models are available, e.g. BS EN 1991-1-2.
Mass transfer	Not applicable	DD ENV 1187 standard test and ad hoc fire tests possible	Suited to expert assessment	Not applicable
Direct pyrolysis and reaction to fire	BS 476-20 (Integrity criteria) (See 7.2.3) Sustained flaming on non-exposed face	Range of standard ignitability tests available	Suited to expert assessment based on knowledge of combustibility	Not available

Figure 8 Potential outputs that can be obtained from various analysis methods

		Conditions/Complexity of analysis					
		Standard resistance tests	Semi-Natural test	Judgement or Assessment in lieu of test	Engineering Calculations		
					 Single element	 Sub - frame	 Entire structure
Thermal Exposure Conditions	Standard time/temperature curves 	REI	REI [†]	REI [†]	RI	R I _{mean} [§]	R I _{mean} [§]
	Experimental curves 	N/A	REI [†]	EI	R I _{mean} [§]	R I _{mean} [§]	R I _{mean} [§]
	Predicted maximum temperature 	N/A	REI [†]	I	R I _{mean} [§]	R I _{mean} [§]	R I _{mean} [§]
	Predicted temperature curves 	N/A	REI [†]	EI	R I _{mean} [§]	R I _{mean} [§]	R I _{mean} [§]

Key

R is the loadbearing capacity criterion (as defined in European standards)

E is the integrity criterion (as defined in European standards)

I is the insulation criterion (as defined in European standards)

I_{mean} is the average temperature rise on homogeneous elements

† 1) restraint: walls – 3 edges restrained, 1 edge free; floor – 2 edges simply supported, 2 edges free;
2) complexity of restraint defined by the experiment;
3) both conventional and bespoke criteria can be determined

§ can be restricted to homogeneous materials

Appropriate fire and structural models should be selected for the scenario under consideration. For example, it is not possible to use the standard fire curve to make an accurate prediction of the performance of a whole-frame structure, but it can be used to compare the relative performance of two different whole-frame structural options. When the element is homogeneous, it might also be possible to predict the possibility of integrity failure, but this is not in absolute terms and the designer should analyse the confidence limits within which the calculated value stands.

7.2 Standard fire resistance tests

7.2.1 General

The results from standardized fire tests are used to obtain comparable information on the ability of constructions to resist the spread of a post-flashover fire under an agreed set of conditions.

When using a prescriptive regulatory approach to ensure the resistance to fire spread of a construction, the performance is measured using a standardized fire exposure or fire resistance test in which the three performance criteria designed to meet the objectives are loadbearing capacity, integrity and insulation, with the last of these requiring the measurement of radiation.

The output obtained from standard fire tests is designed to demonstrate the ability of an element to remain stable and resist excessive deflections for a period of time, and the structure to remain impermeable to the passage of flames, smoke and hot gases 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 the pre-set criteria (see 7.2.5).

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 probably 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 BS 476-20, and there is extensive knowledge of the behaviour of constructions exposed to these specified conditions.

In BS EN 1363-1, the method of measuring the furnace temperature has been changed to a device (plate thermometer) that has a greater thermal inertia than the device (thermocouple) used in BS 476-20. This increases the thermal severity in the fire test furnace so construction elements tested in accordance with BS EN 1363-1 show different results. The designer should be aware of the differences in test regime and their effect on individual building components, as it is not possible to define a 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, 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 could be appropriate to some fire engineered solutions.

An even more extreme exposure test, the jet-fire test, is specified in BS ISO 22899-1, which evaluates structural members and service penetrations that could be exposed to the fire conditions resulting from a failed valve or ruptured pipeline carrying petroleum-based products. This test was designed to simulate off-shore applications and is not designed to replicate any of the conventional built environment conditions, except possibly where liquid petroleum products are being handled.

7.2.2 Application of results of standard tests

The information produced by standardized tests, such as those in BS 476-20 and BS 476-22, are reasonably well understood by the fire safety industry, including the designer, regulators and approving authorities. In most cases, this permits a rapid appraisal to be made of an element's 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 need to understand the relationship between the element tested and the element that exists in the actual building enclosure, or the difference between the expected fire conditions and the test conditions. Where there is a direct similarity between the test specimen and the product used onsite, 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 and/or conditions do not directly correspond with realistic fire conditions and the actual building element. This issue frequently arises, as building components tend to be larger or differently configured to those submitted for fire testing.

The maximum specimen size evaluated under standard test conditions is generally 3 m high × 3 m wide, although a 4 m span is used for evaluating horizontal elements. If standard test data are justified in support of the performance of different constructions, an expert analysis should be carried out on the test results to ensure their suitability for extrapolation. BS ISO/TR 12470 (see 11.4) 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 predetermined criteria: loadbearing capacity, integrity, and insulation. With loadbearing capacity, collapse is obviously the ultimate form of failure. However, an alternative method of judging loadbearing capacity is by exceeding predetermined deflection limits. These are rather arbitrary and they can be exceeded without necessarily causing fire spread. However, satisfying the fire resistance requirement with respect to loadbearing capacity for a period does not imply that the construction is free from deflection. Significant levels of deflection are permitted by failure criteria, as specified in BS 476-20. 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 might be appropriate.

The use of elements of construction that have only been tested under the exposure conditions specified in BS 476-20, BS EN 1363-1, or ISO 834-1 as part of a fire-engineered building design might represent one of the largest compromises to the design that can be made to an otherwise fire safe building. These tests have been recognized in ISO/TR 22898 as having little value to the fire engineering community and ISO/TR 22898 sets out to identify the areas where the tests and their outputs need to be improved if they are to be of greater value to fire engineers.

Whilst ISO/TR 22898 was written to assist those responsible for revising the tests, or for using them in legislation, it provides information to fire safety engineers explaining the areas where the output of the current tests could compromise the fire performance of the design.

7.2.3 Determining the integrity (E) of elements

The integrity criterion used in the standard fire resistance test is difficult to translate into a fire engineering analysis of fire spread, as there are varying degrees of integrity loss that are measured by other criteria. The alternative methods used involve 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 the use of two sizes of gap gauges.

The cotton pad methods have been deemed inappropriate when high levels of radiation are being emitted from the surface, i.e. when the insulation characteristics have been lost, as the pads can ignite as a result of the radiation and not the escaping gases. The two gap gauges used in these situations include the 6 mm diameter gauge,

which should be capable of being moved more than 150 mm before integrity loss is registered, and the 25 mm diameter bar, which just has to pass through the element. These gauges are rigid and BS 476-20 specifies that they have to pass right through from the unexposed to the exposed face before failure is recorded. It is possible for a 200 mm × 25 mm cross-sectional area gap to exist in a construction, but for the construction to satisfy the integrity criterion as long as there is a convoluted path that prevents the gap gauge from passing right through the element. The risk of fire spread due to a loss of integrity is very different when measured by these three methods, and this should be recognized when using integrity as a performance criterion.

7.2.4 Influence of pressure differentials on integrity

Another aspect of integrity measurement is that the test is performed with a predetermined 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 this can sometimes be inappropriate, e.g. 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. If positive pressure is not applied, the duration for which integrity is satisfied can be extended. Positive pressure is also inappropriate for the evaluation of enclosure walls after the roof has been lost. The standard integrity criterion is difficult to apply directly to a fire engineering assessment of fire spread and is often excessively conservative if a purely life safety case is being produced. The proximity of combustible materials, and the sensitivity of equipment being protected, should also feature in the final analysis.

7.2.5 Insulation criterion (I)

The insulation criterion 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 are considered to be safe, although this varies depending upon the fire safety objective as people coming into contact with surfaces at these temperatures risk significant burns. However, if the objective of these limits is to reduce heating of the environment or prevent igniting materials that might be in contact with them, then the traditional temperature levels set are probably lower than the environment can safely tolerate.

7.3 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 can be designed on an ad hoc or project-specific basis or might 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 the designer on a project-specific basis can commission experimental fire tests, the resources needed 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 or chemical or physical changes, then steady state test data could be appropriate.

Enlarging the scale of the experimental test can minimize the differences between the model and the actual element. The use of larger-scale experimental fire tests means that the thermal and mechanical response of the element under examination can be deduced under boundary conditions that approximate to the real building configuration. For example, in experimental tests where levels of continuity and support can be accurately simulated, the observed behaviour is likely to be superior to that suggested in a smaller scale test, or in standardized tests. Equally, simulating the conditions that would prevail in reality through test replication of the actual fire load and ventilation conditions can be more realistic than standard furnace tests where conservative thermal conditions are assumed.

When setting up an experimental test, critical parameters should be selected, e.g. fire load, ventilation, size of test chamber, construction of elements used to form the chamber, external environmental conditions and 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 is to be modelled. As specified in ISO/TR 15658, the written report describing the experimental test should describe and justify all relevant parameters.

Scale-modelling is one of the most difficult aspects of any fire simulation. Most semi-natural tests are smaller than the assembly being replicated. This might not be the case for the actual volume of the fire enclosure, but if this space is within a larger structure 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 can be of a cross-sectional area, or a loading condition that cannot be properly simulated at the reduced scale. As a consequence, most experimental tests incorporate a compromise for 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 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. Whilst reduced fire loads can be used, and it might be possible to alter the size or volume of the material being burnt, almost all flames behave in a similar way if there is a flaming reaction. 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 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.

Any experimental testing undertaken to generate data for a project-specific application, or to establish the response of a product to non-standardized exposure conditions, should follow the procedures specified in ISO/TR 15658. By following the procedures, the results of the tests should be more comparable with data from other experimental testing, thereby extending their applicability.

7.4 Expert assessment

Data about the fire performance of generic boundary elements, obtained from the results of standard fire resistance tests or codes of practice, can be evaluated to permit assessment of the performance of an element within a real building. The results of fire tests can be extrapolated for practical applications in accordance with BS ISO/TR 12470.

Understanding the effect of the scale-difference between the tested specimen and the real building component is one of the most difficult aspects of any expert assessment. The change in scale can apply to dimensional changes, such as height, width, cross-sectional area or boundary conditions, such as applied load and restraint (see 7.3).

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

7.5 Quantitative analysis of fire spread mechanisms

7.5.1 General

Each of the component mechanisms of fire spread can be quantified using engineering models and analysis. However, the level of sophistication available and the reliability of the results achieved varies widely amongst the different mechanisms. This reflects up-to-date understanding and the level of analysis typically required for practical design purposes.

7.5.2 Quantitative analysis of heat flow by conduction

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

$$q_{\text{cond}} = -KA_a \frac{dT}{dN} \quad (1)$$

where:

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

where – indicates that heat always flows from hotter to cooler surfaces.

Heat ceases to flow between areas of equal temperatures. Under steady state conditions where no internal heat is generated, the Laplace equation can be used, where:

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

where x , y , z are the orthogonal directions.

The general equations of conduction can be applied numerically for any particular application using, for example, finite difference or finite element techniques. In some cases exact solutions are available, such as calculating the temperature rise in semi-infinite plane wall exposed to steady heat flux. 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. The designer should 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 such as U-value methods. A range of proprietary computer software is available to allow solution of transient conduction into solid members [4].

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 the heat transfer coefficients of the material. The calculation is simpler if the temperature of the exposed face is known as a result of experimental testing against the appropriate exposure conditions.

If the construction is non-homogeneous it is unlikely a model exists that would enable the unexposed face temperature to be calculated with 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 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, the thermal behaviour can be established using reduced scale specimens. Where delamination at elevated temperatures is likely, unexposed face temperatures can only be established by exposing large specimens to fire. Standard tests available for establishing these measurements are based upon BS 476-20 or BS EN 1363-1.

The fire resistance test represents only one possible fire scenario and one set of exposure conditions and, in reality, unexposed face temperatures can vary from the conditions measured in the test. The thermal properties could also be influenced by the rate of heating.

Based upon the quantity of heat being conducted through 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 dependent on small-scale experiments that might not be readily scalable to real building assemblies. 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 the failure criteria in BS 476-20.