PUBLISHED DOCUMENT

PD 7974-1:2003

Application of fire safety engineering principles to the design of buildings —

Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)

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Contents

Foreword

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

— *Part 0: Guide to design framework and fire safety engineering procedures*;

— *Part 2: Spread of smoke and toxic gases within and beyond the enclosure of origin (Sub-system 2)*;

— *Part 3: Structural response and fire spread beyond the enclosure of origin (Sub-system 3)*;

— *Part 4: Detection of fire and activation of fire protection systems (Sub-system 4)*;

— *Part 5: Fire service intervention (Sub-system 5)*;

— *Part 6: Evacuation (Sub-system 6)*;

— *Part 7: Probabilistic risk assessment*.

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

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

Drafting of this publication was completed in July 2001.

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

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

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Introduction

This Published Document is one of a series of documents intended to support BS 7974. The Code of Practice provides a framework for developing a rational methodology for design using a fire safety engineering approach through the application of scientific and engineering principles to the protection of people, property and the environment from fire.

The Published Documents (PDs) contain guidance and information on how to undertake quantitative and detailed analysis of specific aspects of the design. They are a summary of the "state of the art" and it is intended that they be updated as new theories, calculation methods and/or data become available. They do not preclude the use of appropriate methods and data from other sources. Figure 1 shows the structure of the Code of Practice and the Published Documents.

BS 7974 can be used to define one or more fire safety design issues to be addressed using fire safety engineering. The appropriate PDs can then be used to set specific acceptance criteria and/or undertake detailed analysis.

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

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

a) provide the designer with a disciplined approach to fire safety design;

b) allow the safety levels for alternative designs to be compared;

c) provide a basis for selection of appropriate fire protection systems;

d) provide opportunities for innovative design;

e) provide information on the management of fire safety for a building.

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

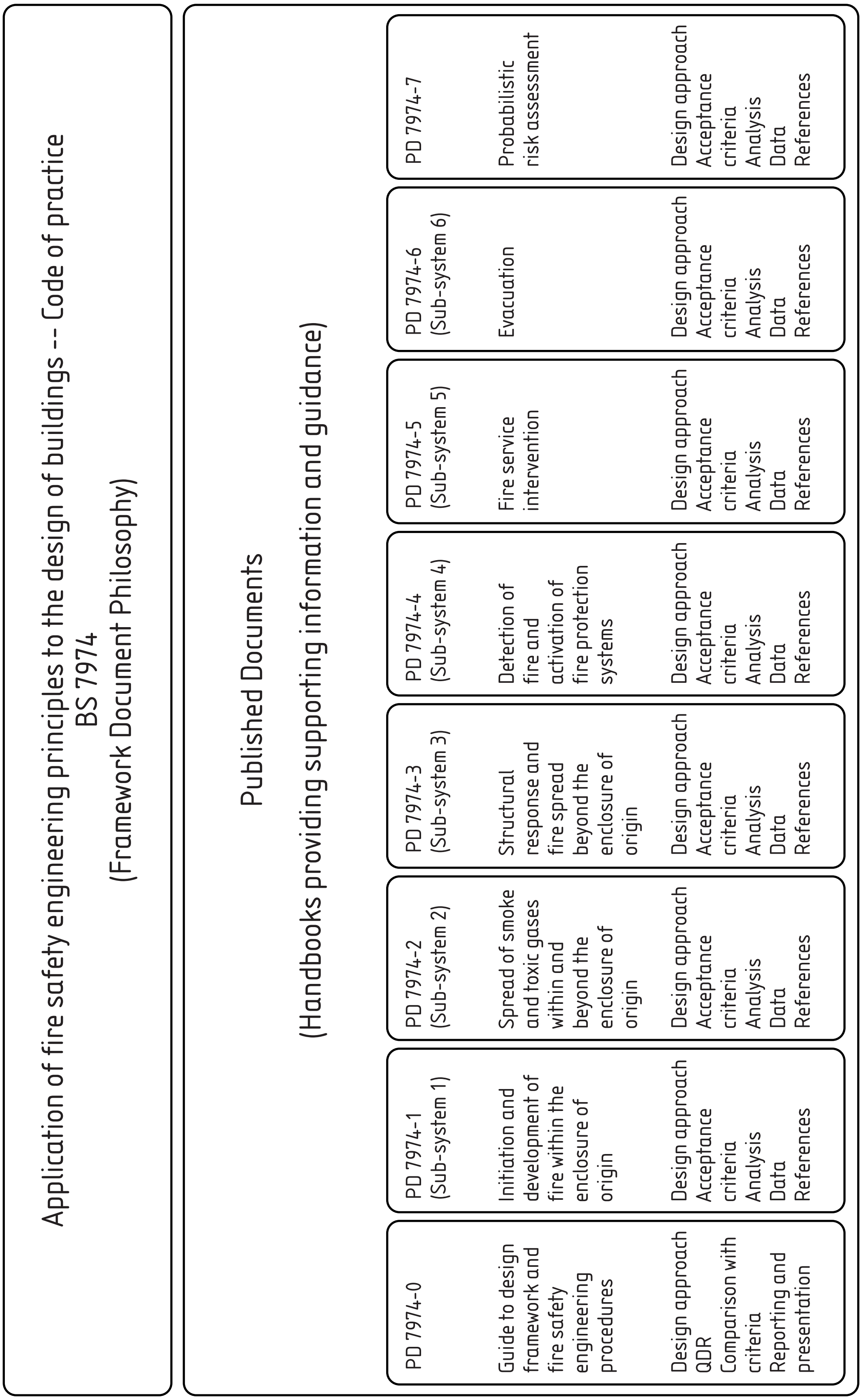


Figure 1 — Overview of the PD 7974 series of Published Documents

1 Scope

This Published Document provides guidance on evaluating fire growth and/or size within the enclosure of fire origin, as well as enclosures to which the fire has subsequently spread. Guidance is also provided for “special cases” which include malicious fires, racked/stacked storage of goods and fires external to the building.

The characteristics of the design fire for any particular scenario are influenced by a number of factors, including building design, environmental influences, potential ignition sources and location, types of combustible materials, distribution and arrangement of combustible materials, ventilation conditions and other events occurring during the fire.

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

2 Normative references

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

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

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

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

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

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

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

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

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

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

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

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

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

3 Terms and definitions

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

3.1
calorific value

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

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

3.2
compartment
space defined by fire resisting boundary elements

3.3
critical fire load
fire load required in a compartment to produce a fire of sufficient severity to cause failure of fire resisting barriers or structural elements

3.4
deterministic study
methodology based on physical relationships derived from scientific theories and empirical results, that for a given set of initial conditions will always produce the same outcome

3.5
effective calorific value
moisture corrected value obtained by calculation

3.6
effective fire load density
fire load density within an enclosure or compartment modified by factors that take account of the incomplete combustion of protected fire loads and/or a reduction in the net quantity of heat released resulting from the presence of wet materials

3.7
enclosure
space defined by boundary elements (on all sides) around the point of origin of the fire

3.8
equivalent fire load density
fire load density expressed as an equivalent mass of wood rather than in terms of its calorific value

3.9
fire hazard
source for potential loss of life (or injury) and/or damage to property by fire

3.10
fire load
sum of the calorific energies, which could be released by the complete combustion and all the combustible materials in a space including the facing of the walls, partitions, floors and ceilings

3.11
fire load density
fire load divided by the floor area

3.12
fire risk
product of:

a) probability of occurrence of a fire to be expected in a given technical operation or state in a defined time; and

b) consequence or extent of damage to be expected on the occurrence of a fire

3.13
fire scenario
qualitative description of the course of a fire with time, identifying key events that characterize the fire and differentiate it from other possible fires

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

3.14

fire size

heat release rate of the fire

3.15

flashover

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

3.16

gross heat of combustion

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

3.17

mixed use building

building where different parts are used for different purposes

3.18

multiple use building

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

3.19

probabilistic study

methodology to determine statistically the probability and outcome of events

3.20

protected fire load

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

NOTE For example, steel filing cabinets.

3.21

smouldering fire

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

4 Symbols and abbreviations

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

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

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

θ	is the temperature rise above ambient in the upper gas layer (°C)
λ_f	is the thickness of the flame (m)
ρ	is the density of the enclosure boundaries ($kg \cdot m^3$)
ρ_0	is the ambient air density (kg/m^3)
σ	is the Stefan-Bolzmann constant (5.67×10^{-11} $W \cdot m^{-1} \cdot K^{-1}$)
ϕ	is the configuration factor (dimensionless)
χ	is the fraction of the total heat release rate convected by the plume (dimensionless)

5 Design approach

5.1 Experience and qualifications

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

5.2 Framework

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

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

Sub-system 1 concentrates on the quantification judgements that can form the part of the design process in which the initiation and development of the fire are defined. The calculation methods and data contained in this Sub-system are included with the known limitations. Alternative data and calculation methods are not precluded and might be required. Satisfactory justification of any calculation method or approach selected should always be provided.

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

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

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

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

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

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

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

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

Sub-systems

Key
● Likely interactions
○ Potential interactions

Figure 2 — Sub-system interactions

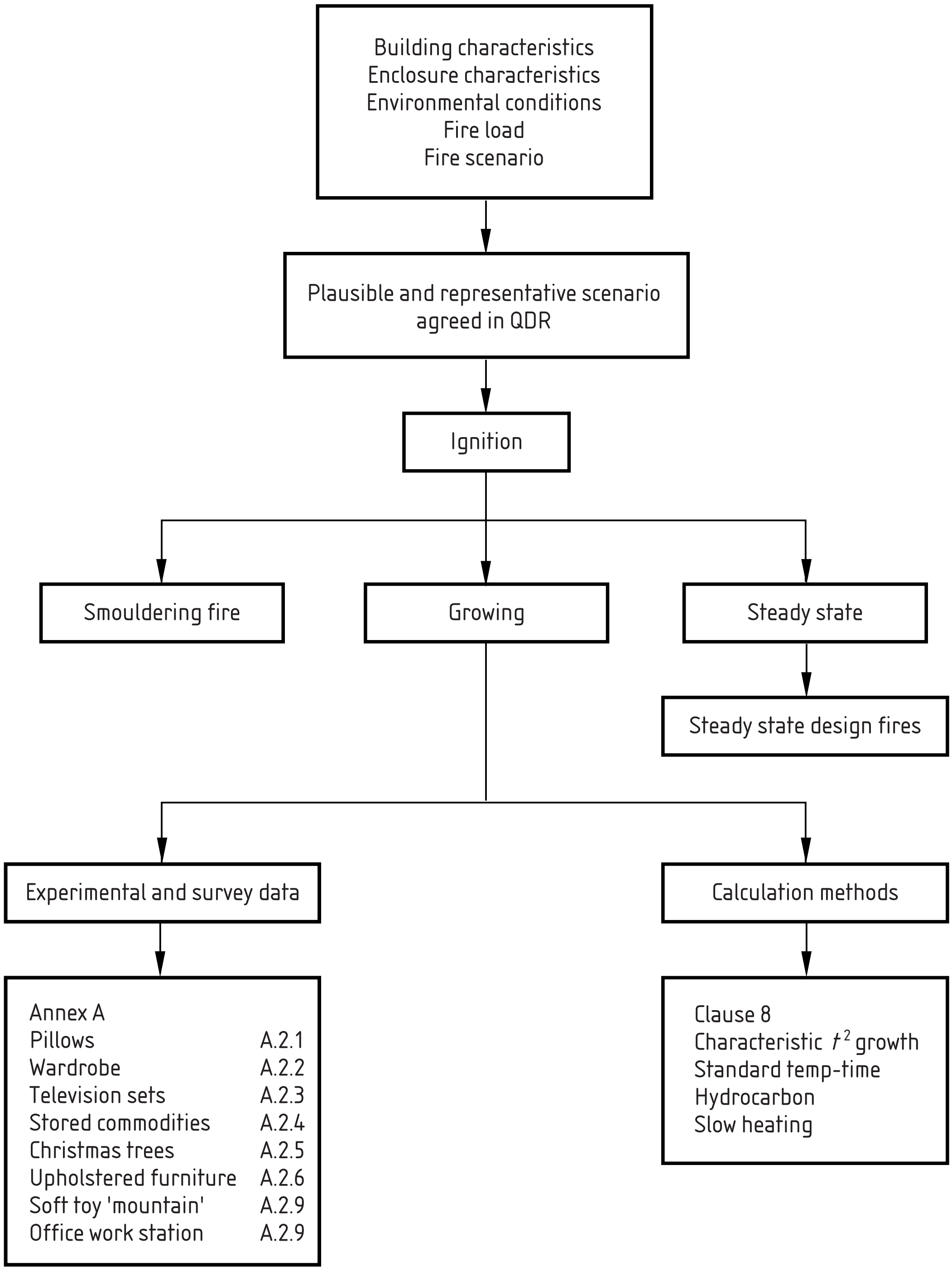


Figure 3 — Flow chart showing the initial steps that should be taken in the process of selecting fires appropriate to a particular design

5.3 Design fires

The characteristics of a design fire for any particular scenario are influenced by a number of factors including building design, environmental influences, potential ignition sources and location, types of combustible materials, distribution and arrangement of combustible materials, ventilation conditions and other events occurring during the fire.

The design fire may be characterized in terms of:

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

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

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

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

5.4 Building characteristics

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

a) building:
   1) dimensions of construction/building;
   2) geometry of construction/building;
   3) nature of construction of building (materials and method).

b) enclosure:
   1) wall and ceiling linings;
   2) ventilation conditions (natural and/or mechanical);
   3) unusual fire hazards;
   4) potential ignition sources.

5.5 Fuel load

Information on fuel load will be provided from the QDR and consideration, in terms of the potential consequences, should be given to the contributions from all relevant factors influencing the fire growth process which include:

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

5.6 Environmental influences

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

a) internal ambient temperatures;

b) internal ambient air movement.

5.7 Fire load

5.7.1 *General*

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

A fire load can be composed of:

a) permanent fire loads (combustible materials including load bearing structure, linings, finishes);

b) variable fire loads (combustible materials which vary during the life of the building);

c) protected fire loads (combustible materials protected against exposure to fire i.e. low probability of involvement in the fire);

d) unprotected fire loads (combustible materials not protected).

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

5.7.2 *Fire load density*

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

$$q_{\mathrm{k}} = \sum \frac{m_{\mathrm{c}} H_{\mathrm{c}}}{A_{\mathrm{f}}}$$

where

q_{k}	fire load density for the enclosure (MJ/m^2)
m_{c}	total mass of each combustible material in the enclosure (kg)
H_{c}	effective calorific value of each combustible material (MJ/kg)
A_{f}	total internal floor area of the enclosure (m^2)

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

$$H_{\mathrm{c}} = H_{\mathrm{u}}(1 - 0.001M) - 0.025M$$

where

H_{u}	calorific value of dry material (MJ/kg)
M	moisture content (% by dry mass)

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

5.8 Time to flashover

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

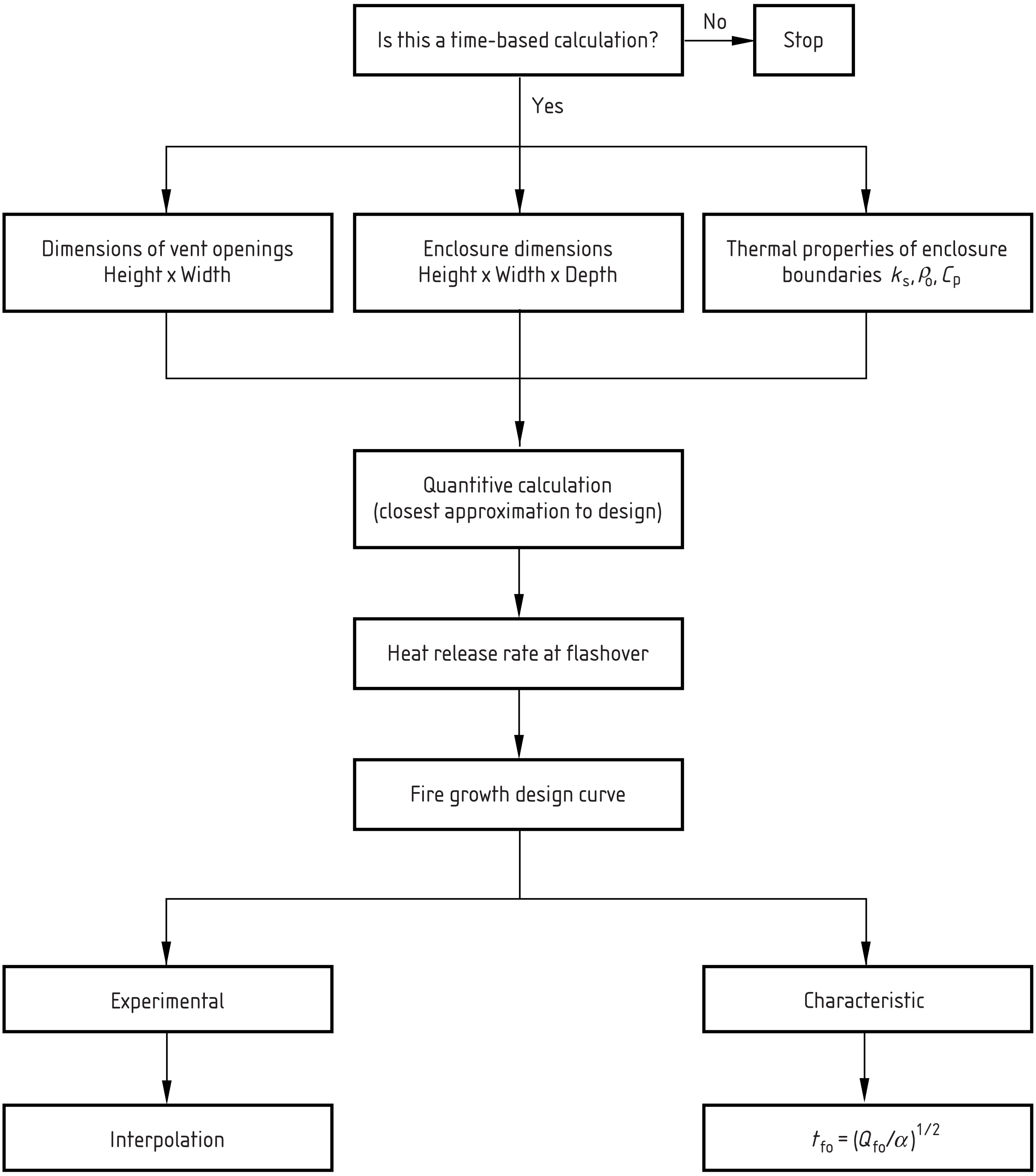


Figure 4 — Calculation process of time to flashover

5.9 Sensitivity analysis

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

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

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

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

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

The objective of a sensitivity study is to establish the impact on the output parameter(s) caused by variation in the input parameter(s), it is not intended to check the accuracy of the results.

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

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

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

6 Inputs

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

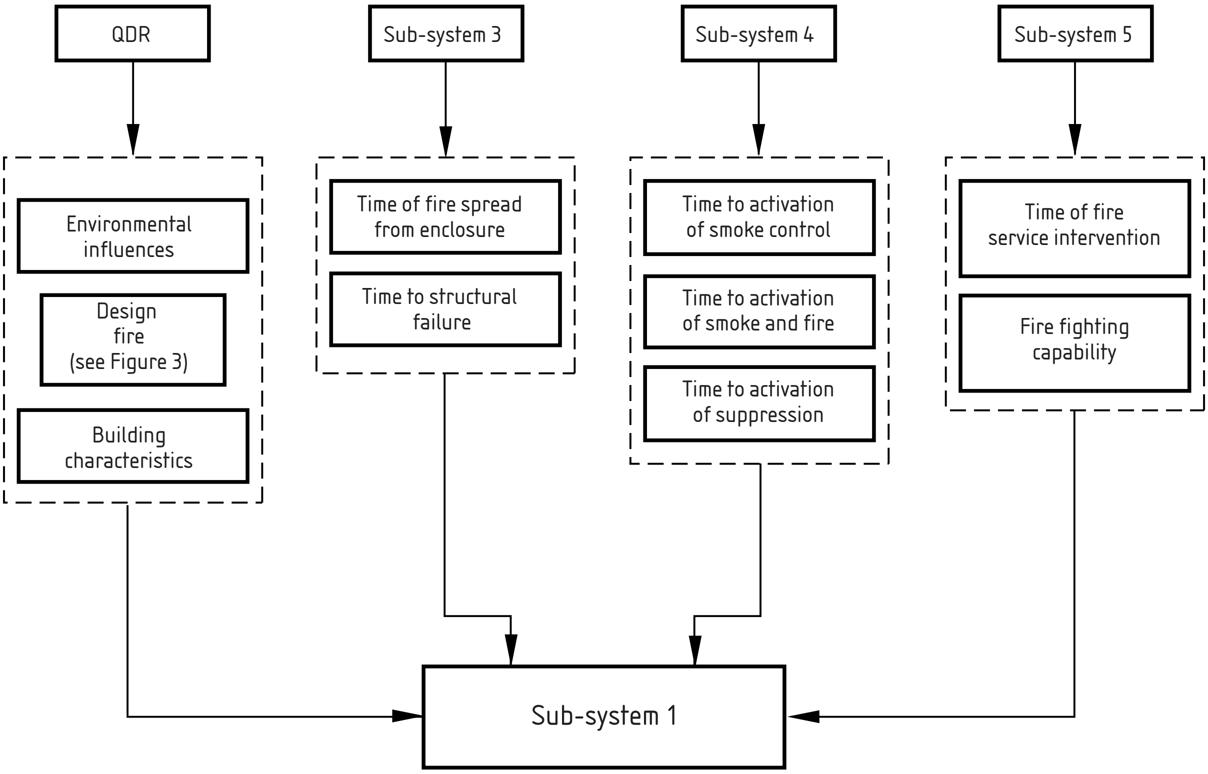


Figure 5 — Sub-system 1 inputs

7 Outputs

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

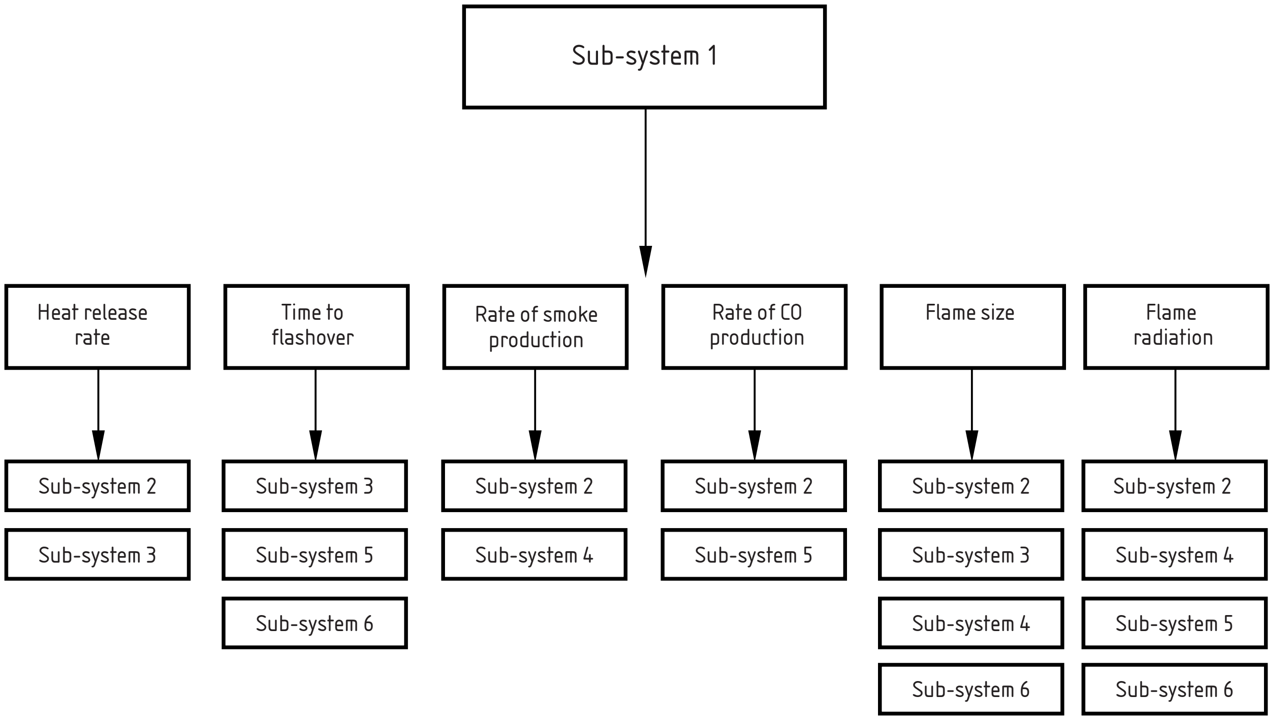


Figure 6 — Sub-system 1 outputs

8 Analysis

8.1 Classification

8.1.1 *General*

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

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

It should be noted that flashover does not necessarily occur.

8.1.2 *Ignition*

Ignition generally leads to the initiation of flaming combustion. Whilst methods for quantifying the ignitability or ease of ignition of materials under well defined conditions exist, there are currently no general deterministic methods available for predicting the potential for ignition.

The design approach typically adopted is to consider the potential ignition sources that are present. These may include:

- smokers' materials;
- naked flames;
- electric, gas or oil heaters;
- hot working;
- cooking;
- engines or boilers;
- machinery or office equipment;
- lighting equipment;
- friction from drive belts;
- reactive dusts;
- static electricity;
- metal impact;
- arson.

Consideration should then be given to the most probable ignition source, location and fuel likely to be first ignited. The presence or not of a "pilot" such as a spark or independent flame can have a significant influence on the ignition process.

8.1.3 *Pre-flashover or fire growth*

This can be either a smouldering or flaming stage (see **8.1.4** and **8.1.5**).

8.1.4 *Smouldering*

Smouldering is a slow, flameless form of combustion, which is generally poorly ventilated producing very little heat but having the potential to fill an enclosure with unburned combustible gases together with combustion products including, toxic gases and smoke particles. If the room is suddenly ventilated then very rapid ignition can occur. If the ignition gives rise to a deflagration then this process is described as a backdraught or smoke explosion.

The following factors effect the likelihood of onset of smouldering combustion:

- nature of the fuel;
- ventilation limitations;
- strength of ignition source.

As a result of incomplete combustion, carbon monoxide (CO) is the principal hazard associated with smouldering combustion. The onset of untenable conditions due to poor visibility is also a significant hazard that should be considered.

It should be assumed that a smouldering fire would not activate sprinklers. To be effective against smouldering fires, suppression systems need to be coupled to appropriate detection systems. It is important to realize that the smoke from fires of low heat release rate such as smouldering fires will be simply transported as "passive" contaminants in the ambient air currents. Detection systems need to be located with this in mind.

Smouldering fires can easily transform into flaming fires particularly when ventilation is increased. Once the transition from a smouldering to a flaming fire has occurred, the evaluation procedure for flaming fires applies.

8.1.5 *Flaming*

The rate of fire growth of a flaming fire in the pre-flashover stage can be determined by considering the following:

- — item first ignited;
- — flame spread;
- — potential for fire spread from item to item;
- — radiation;
- — convection;
- — conduction;
- — potential for fire spread due to re-radiation from the ceiling layer;
- — wind effects;
- — effect of suppression systems.

During this pre-flashover stage there is an energy feedback from the flames which causes further pyrolysis of the item. This then produces further flaming which in turn produces greater pyrolysis of the item.

After the item has been ignited the likelihood of transition to the established burning phase needs to be considered. The following parameters are relevant in determining if there is sufficient energy for sustained burning:

- — energy of ignition source;
- — potential for flame spread;
- — rate of heat release and flame characteristics from ignited items;
- — geometry/configuration of ignited item;
- — energy losses particularly due to conduction.

The duration of this incipient stage is difficult to predict accurately and is usually not quantified in engineering calculations of development of untenable conditions. The length of the stage depends on the intensity of the ignition source and the nature of the fuel. Experimental work involving particular scenarios might provide some guidance on the duration of this incipient stage.

Fire growth during the pre-flashover stage is illustrated in Figure 7.

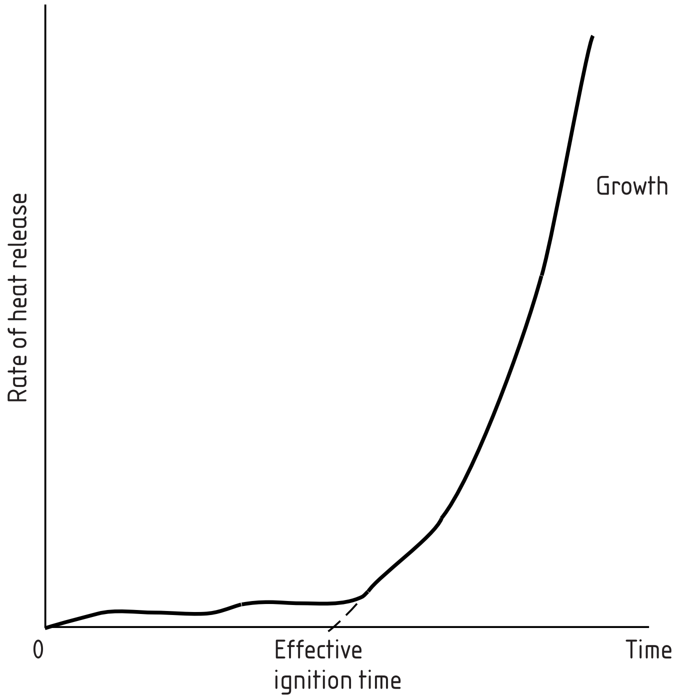


Figure 7 — Conceptual illustration of continuous fire growth

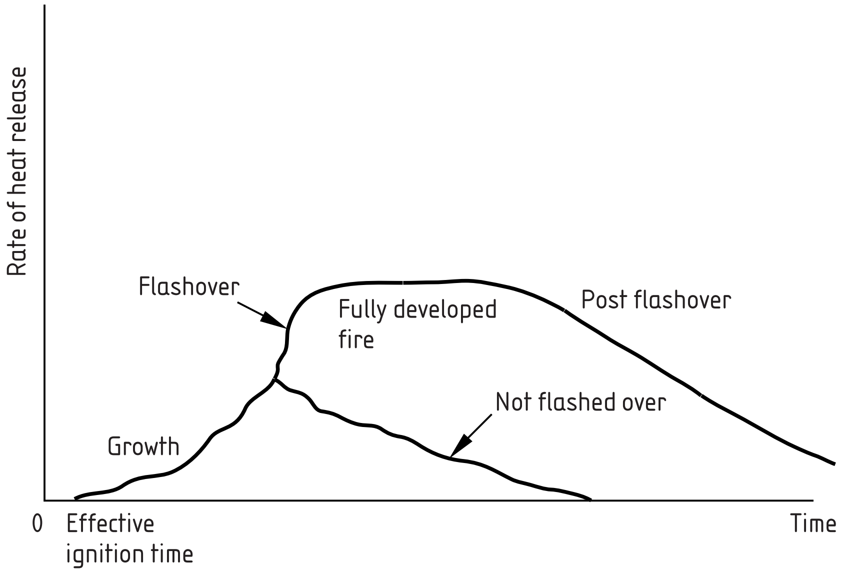


Figure 8 — Fire growth in an uncontrolled room fire

8.1.6 *Flashover*

Flashover can be assumed to occur when sustained flaming from combustibles reaches the ceiling and the temperature of the hot gas layer is between 550 °C and 600 °C. If flames from the combustibles do not reach the ceiling, or the temperature remains below 550 °C, flashover can be assumed to be unlikely.

After flashover, the rate of heat release will increase rapidly until it reaches the maximum value for the enclosure. To simplify design, the growth period between the onset of flashover and the maximum heat release rate is usually ignored, and it can be assumed that when flashover occurs the rate of heat release instantaneously increases to the maximum value set by the availability of air.

This assumption, which is made in Figure 9, is conservative in relation to its estimation of the maximum heat release rate. However, it should be noted that for other stages of the design calculation, this assumption might not be conservative at all e.g. for calculation of the time to activation of fire detection and suppression systems.

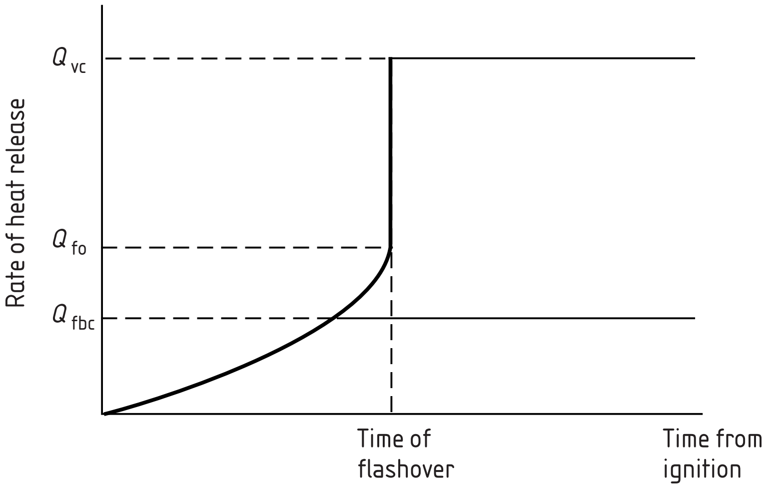
8.1.7 *Fully developed fire*

The fully developed fire is the stage at which all of the available fuel is burning. During the fully developed stage of the fire, the maximum rate of heat release may be controlled by either the available ventilation or the quantity and nature of the fuel. The heat release rates for both ventilation-controlled and fuel-bed-controlled regimes should be calculated and the dominant regime taken as representing the fully developed fire.

8.1.8 *Ventilation controlled regime*

The available ventilation imposes an upper limit on the rate of burning. If the available ventilation is restricted, the fire may not reach the flashover stage and in some cases may self-extinguish. Where flashover does occur, the heat release rate rises to the maximum possible with the available ventilation. (See Figure 9.)

During the course of the fire there might be an increase in ventilation. This could be due to windows breaking, fire service intervention or the operation of the air handling or smoke extract systems. For design purposes, it might be necessary to estimate the time at which such changes may occur and the influence they may have on fire growth rate and its severity. One possible approach to this is to assume a characteristic fire profile and then include events such as window breakage by calculating the effect of increase in ventilation on the profile of the fire.



Q_{vc} is the rate of heat release under ventilation-controlled conditions
Q_{fo} is the rate of heat release at flashover
Q_{fbc} is the rate of heat release under fuel-bed controlled conditions

Figure 9 — Heat release rate curves for uncontrolled fires

8.1.9 *Fuel-bed controlled regime*

In a fuel-bed controlled fire, the combustibles are able to burn freely and the rate of heat release is limited by the amount, type and surface area/orientation of the burning items. With a small amount of fuel, or with slow-burning materials, the rate of heat release can be too low to produce flashover even when all the items are burning. Where flashover does occur, the heat release rate eventually rises to the maximum free-burning value. (See Figure 9.)

8.1.10 *Decay*

For design purposes, it may be assumed that the heat release rate remains constant until 70 % of the fuel has been consumed. In a majority of cases, analysis after this time is unnecessary.

8.1.11 *Effect of suppression*

During the pre-flashover stage, there can be intervention by first-aid fire-fighting or automatic suppression, or by the fire service. The fire service can also intervene after flashover. The effectiveness of the suppression system depends on several factors, including:

a) the fire size at the time of suppression system activation;

b) the type of suppression system;

c) the characteristics of the suppression system;

d) the geometry of the protected space;

e) the extent to which the fuel is shielded from the suppression medium.

Five of the possible effects of suppression that should be considered for design purposes are as follows:

a) the application of the extinguishing agent reduces the rate of heat release effectively to zero extinguishing the fire; see (a) Figure 10;

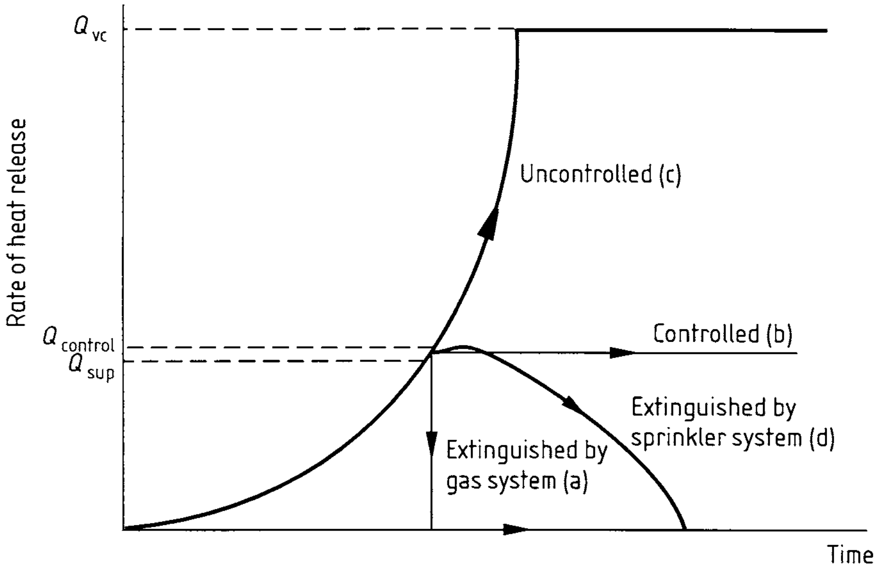
b) the application of the extinguishing agent halts the increase in the rate of heat release, and the fire then continues to burn at a constant rate; see (b) Figure 10. In some design applications, it is typical to assume that the fire is steady state from ignition. More guidance can be found in **8.2.1.6**. Other possibilities after application of the extinguishing agent at Q_{sup} are as follows. These are illustrated in Figure 11.

c) fire continues to grow but more slowly than before [see (e) Figure 11];

d) fire is suddenly reduced in rate of heat release, but continues to grow more slowly [see (f) Figure 11];

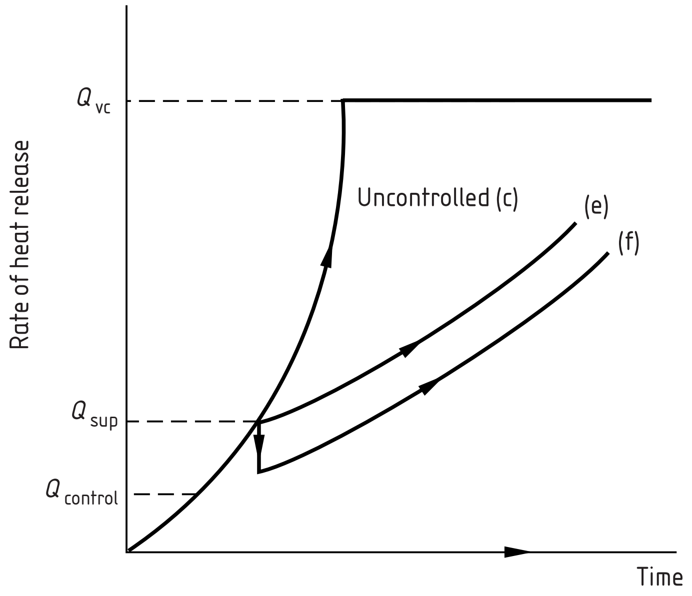
e) the probability of failure of installed automatic suppression systems should be considered when determining if a fire is likely to be uncontrolled. The uncontrolled fire should also be considered when looking at the effect of first aid fire-fighting.

Guidance on the quantitative effects of suppression systems on fire growth can be found in Sub-system 4.



Q_{vc} is the rate of heat release under ventilation-controlled conditions
Q_{sup} is the rate of heat release at which suppression activates
$Q_{control}$ is the rate of heat release at which the fire can be controlled

Figure 10 — Effect of suppression



Q_{vc} is the rate of heat release under ventilation-controlled conditions
Q_{sup} is the rate of heat release at which suppression activates
$Q_{control}$ is the rate of heat release at which the fire can be controlled

Figure 11 — Effect of partial suppression

8.2 Design calculations

8.2.1 *Pre-flashover stages of the fire*

8.2.1.1 *Q — Heat release rate*

The amount of heat released by a fire per unit of time depends on its heat of combustion and the mass of fuel burned per unit time.

$$Q = m_f \Delta H_c \qquad (1)$$

where

Q	total heat release rate (kW)
m_f	mass loss rate of fuel (kg/s)
ΔH_c	heat of combustion (kJ/kg)

NOTE *Limits*. This equation assumes complete combustion of the vaporized fuel. In vitiated conditions, there is significant incomplete combustion, particularly for ceiling fires and caution should be used when applying this equation to calculate heat release rates.

8.2.1.2 Q_p — *Convective heat release*

The convective heat output of the plume is dependent upon the luminosity of the flame. The less luminous the flame the greater the convective heat output, i.e. "clean burning" fuel — alcohol — will have a greater convective heat output.

The convective heat output of the plume is given by:

$$Q_p = \chi Q \quad (2)$$

where

Q_p heat release rate convected by the plume (kW)

Q total heat release rate (kW)

χ is the fraction of the total heat release rate convected by the plume. This can range from 0.4 to 0.9 depending upon the fuel

Data for particular fuels can be found in SFPE Handbook of Fire Engineering [2]

8.2.1.3 *Q* — Dimensionless heat release rate*

*Q** is a dimensionless heat release rate first introduced by Zukoski [3]. It is a relative measure of the importance of inertia and buoyancy expressed in terms of heat release rate of the fire. It is used to classify fire types and correlate aspects of fire behaviour, such as flame height, air entrainment and soot production.

$$Q^* = \frac{Q}{\rho_0 C_p T_0 g^{1/2} D_s^{5/2}} \text{ or } \frac{Q}{1110 D_s^{5/2}} \quad (3)\ [4]$$

for “normal” ambient conditions, where

Q is the total heat release rate (kW)

C_p is the specific heat capacity ($\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$)

ρ_0 is the ambient air density ($\mathrm{kg \cdot m^{-3}}$)

T_0 is the ambient air temperature (K)

g is the acceleration due to gravity ($\mathrm{m \cdot s^{-2}}$)

D_s is the linear dimensions of the source (m)

For buoyant fires *Q** will typically be less than 2.

8.2.1.4 *Characteristic fire growth curve — t^2*

The growth phase of many fires can be characterised as increasing proportionally with the square of time (Evans [5]) measured from an ignition reference time, t_i, as

$$Q = \alpha(t - t_i)^2 \quad (4)$$

where

Q is the total heat release rate from the fire during the growth phase (kW)

t is the time from ignition (s)

t_i is the time of ignition (s)

α is the fire growth parameter ($\mathrm{kJ/s^3}$)

In an extensive series of tests carried out by Factory Mutual Research Corporation, measurements were made of maximum ceiling jet temperatures and velocities during the growth of fires in which various wood cribs were burned. The ceiling jet temperature and velocity correlations are the basis for the calculated values of fire detector spacing found in NFPA 72E, Standard on Automatic Fire Detectors, and the value of fire detector response times calculated by special publications of the U.S. National Bureau of Standards. In these publications, three or four selected fire energy release rates assumed to increase proportionally with the square of time were used as the basis for the evaluation. These fire energy release rate histories were chosen to be representative of actual fire situations involving different commodities and geometric storage arrangements. These fire growth parameters are given in Table 2.

Table 2 — Fire growth parameters [6]

Classification	α
Slow	0.002 9
Medium	0.012
Fast	0.047
Ultra-fast	0.188
NOTE *Limits.* The t^2 parameters represent fire growth starting with a reasonably large flaming ignition source. With a smaller source, there is an incubation period before established flaming occurs.	

Table 3 — Design fire growth rates

Building use	Fire growth rate
Picture gallery	Slow
Dwelling	Medium
Office	Medium
Hotel reception	Medium
Hotel bedroom	Medium
Shop	Fast
Industrial storage or plant room	Ultra-fast
NOTE *Limits.* The characteristic fire growth rates given in Table 2 should be used for general design purposes for different types of occupancies. For multiple use buildings, the faster growth rate should be taken.	

8.2.1.5 *Heat release rate per unit area*

If the likely rate of heat release per unit area can be established for the particular use of a building, the rate of heat release may be calculated from the area of the room or compartment (or vice versa) by means of the following equation:

$$Q = Q'' A_{\mathrm{fire}} \qquad (5)$$

where

Q is the total heat release rate from the fire (kW)

Q'' is the total heat release rate per unit area of fire (kW/m^2)

A_{fire} is the area of fire (m^2)

Table 4 — Suggested heat release rates per unit area for fuel bed controlled fires

Occupancy	Heat release rate per unit area kW/m^2
Shops [5]	550
Offices [5]	290
Hotel Rooms [5]	250
Industrial [7]	90 – 620
Excluding storage	depending upon fuel and arrangement
NOTE *Limits.* This information should be treated with care, as it is predominantly of US origin and therefore may not always be representative of UK occupancies.	

8.2.1.6 *Steady state design*

It is necessary to assess the largest fire that can be expected in the period of interest. This would include the effect of fire suppression action by sprinklers, or the fire service or any other agent or system. When this leads to unsafe conditions additional protection is necessary. For smoke control design a steady state fire is normally assumed, based on this largest fire.

For information on the origins of the steady state design fire, see Law [8].

8.2.1.7 *Smouldering fire*

Quintiere *et al.* [9] has developed a model for smouldering fires. This model describes the pyrolysis rate by the expression:

$$m = \begin{cases} (0.10\ \mathrm{g\ min^{-1}})\ t + (0.018\ 5\ \mathrm{g\ min^{-3}})\ t^2 & 0 \le t \le 60\ \mathrm{min} \\ (73\ \mathrm{g\ min^{-1}}) & 60 \le t \le 120\ \mathrm{min} \end{cases} \qquad (6)$$

where

m is the smouldering pyrolysis rate (g/min).

NOTE *Limits*. The expression is an experimental smoulder rate and is only valid for the two NBS tests, T18 polyurethane and T22 cotton. The validity of this equation was also confirmed [10] by comparison with Bill and Kung's [11] full-scale experimental data.

8.2.1.8 *Calculations from first principles*

The heat release of the item first ignited should be determined from the specific data (for examples, see Annex A). An analysis should be performed to ascertain if the fire is likely to spread to neighbouring items. This can be accomplished by considering the radiant heat transfer from the flames to adjacent fuel items. The radiant heat flux incident on the adjacent packages should be compared with the critical ignition fluxes for the relevant materials to determine if secondary ignition (fire spread) is likely.

8.2.1.9 *Experimental data*

Results from experimental fire test data may be used as a direct source of heat release data for fire models, provided the limitations of the tests are considered. Much information on burning rates for single items has been reported under free burning conditions in large enclosures. Such data do not usually include the effects of:

a) radiative feedback from the hot smoke layer or from the enclosure surfaces;

b) limited supply of oxygen due to ventilation conditions or the flame becoming immersed in the layer of combustion products;

c) interaction between objects, particularly their orientation and storage.

Tables of data can be found in Annex A.

8.2.1.10 *Temperature within enclosure prior to flashover*

This method uses a zone model concept and assumes a uniform hot gas layer that collects under the ceiling. Such methods do not predict the local temperatures, which determine when a detector or sprinkler will be triggered. The following relationship is derived from experimental data, by McCaffrey, Quintiere, Hakleroad [12]. It can be used to calculate the temperature rise above ambient in the enclosure prior to flashover, provided that the upper gas layer does not exceed between 500 °C to 600 °C, based on the assumption that flashover occurs at an upper layer temperature rise of between 550 °C to 600 °C [13]. A conservative approach in relation to fire growth would be to assume a value of 550 °C.

$$Q = 6.85 \left(\frac{Q^2}{A_\mathrm{w} h^{1/2} h_\mathrm{k} A_\mathrm{t}} \right)^{1/3} \qquad (7)$$

NOTE 1 The enclosures were in the range of 0.3 m to 2.7 m high by 0.14 m^2 to 12 m^2 floor area.

For the case where the thermal penetration time, t_p, for the enclosure boundaries is greater than the fire exposure time, i.e. heat transfer is transient or non-steady:

$$h_k = \left(\frac{k_s \rho c_{ps}}{t_p}\right)^{1/2} \tag{8}$$

and

$$t_p = (\rho c_{ps}/k_s)(\delta/2)^2 \tag{9}$$

or for the case where the thermal penetration time for the enclosure is significantly shorter than the fire exposure time, i.e. heat transfer is steady:

$$h_k = k_s/\delta \tag{10}$$

where

θ is the temperature rise above ambient in the upper gas layer (°C)
Q is the total rate of heat release (kW)
A_t is the total surface area of the enclosure (m^2)
A_w is the area of the ventilation opening (m^2)
h_k is the effective heat transfer coefficient (kW·m^{-2}·K^{-1})
h is the height of the ventilation opening (m)
k_s is the thermal conductivity of the enclosure boundaries (kW·m^{-1}·K^{-1})
ρ is the density of the enclosure boundaries (kg·m^3)
c_{ps} is the specific heat capacity of the enclosure boundaries (kJ·kg^{-1}·K^{-1})
δ is the thickness of the enclosure boundaries (m)
t_p is the thermal penetration time (s)

NOTE 2 *Limits* (see DD 240-2:1997). Equation (7) is only valid when a two-dimensional flow has been established in the vertical ventilation opening(s) i.e. the equation is not applicable to the smoke-filling phase of an enclosure fire process. The model assumes a hot gas layer of uniform temperature. It is not applicable to fire process controlled by ventilation. Special care has to be taken:

a) when the fire enclosure has more than one opening;

b) for a very well-insulated fire enclosure or in other situations when $h_k \to 0$;

c) when fire growth is extraordinarily fast;

d) for fires in corners or adjacent to a wall;

e) for complicated fire room geometries.

8.2.1.11 *Heat release rate at flashover*

There are two methods of calculation:

a) Method 1

Thomas [14] developed an analysis basing the heat flow through an opening on a mass inflow expressed in terms of ventilation control. The rate of heat release required for flashover to occur, which is based upon the assumption that flashover occurs at an upper-layer temperature rise of 600 °C, is:

$$Q_{fo} = 7.8A_t + 378A_w h^{1/2} \tag{11}$$

where

Q_{fo} is the rate of heat release at flashover (kW)
A_t is the total surface area of the enclosure (m^2)
h is the height of ventilation openings (m)
A_w is the area of ventilation openings (m^2)

Where the effects of thermal properties of the linings are to be considered, the following equation, by McCaffrey *et al.* [4], may be used in place of the equation above:

$$Q_{fo} = 750(h_k A_t A_w h^{1/2})^{1/2} \tag{12}$$

where

Q_{fo} is the rate of heat release at flashover (kW)
h_k is the effective heat transfer coefficient ($kW \cdot m^{-2} \cdot K^{-1}$)
A_t is the total surface area of the enclosure (m^2)
A_w is the area of ventilation openings (m^2)
h is the height of ventilation openings (m)

NOTE 1 The enclosures were in the range of 0.3 m to 2.7 m high by 0.14 m^2 to 12 m^2 floor area.

NOTE 2 *Limits* [12]. Equations (11) and (12) are only valid when a two-dimensional flow has been established in the vertical ventilation opening(s) i.e. the equations are not applicable to the smoke-filling phase of an enclosure fire process. The models assume a hot gas layer of uniform temperature. They are not applicable to fire process controlled by ventilation. Special care has to be taken:

1) when the fire enclosure has more than one opening;
2) for a very well-insulated fire enclosure or in other situations when $h_k \to 0$;
3) when fire growth is extraordinarily fast;
4) for fires in corners or adjacent to a wall;
5) for complicated fire room geometries.

In addition, the models are based on experiments with wall material of relatively high thermal inertia and can be less conservative for highly insulated fire compartments.

b) Method 2

By choosing a temperature rise of 500 °C as the flashover temperature and substituting this into equation (7), McCaffrey *et al.* derived the expression for the necessary heat release rate to cause this temperature rise, i.e. flashover. This equation differs from method (equation 11) in that it includes explicitly heat transfer through the compartment boundaries.

$$q = 610\left(h_k A_w A\sqrt{H}\right)^{1/2} \tag{13}$$ [12]

where

q is the necessary heat release rate to cause the temperature rise (kW)

h_k is the effective heat transfer coefficient ($kWm^{-2} \cdot K^{-1}$)

A_w is the area of ventilation openings (m^2)

H is the height of ceiling above the fire source (m)

A is the opening area (m^2)

NOTE 3 *Limits*. McCaffrey *et al*. [12] stated that they had not included "extensive data" from ventilation-controlled fires, and that all data were for fires near the centre of a room. They do not give any data on the fire perimeters. The enclosures used had dimensions summarized in Table 5. It can be seen that almost all the openings were taller than they were wide, and that some were very narrow indeed. It is, therefore, significant that McCaffrey *et al*. [12] included a caution that their correlation might be less relevant for "very different" experiments.

It should be stated that caution should be used with these equations and they should only be used where a compartment is similar to the experimental compartments.

Table 5 — Experimental enclosure quoted by McCaffrey *et al.* [12]

Enclosure			Opening	
Height m	Width m	Length m	Height m	Width m
0.30	0.30	0.56	0.225	0.15 to 0.285
2.41	2.18	2.18	1.83	0.2 to 0.79
2.44	3.40	3.52	2.13	0.91
2.3	3.0	3.0	1.93	0.73
0.41	0.39	0.37	0.29	0.11
2.7	2.9	3.75	1.3	0.15 to 1.2
2.4	2.4	3.6	2.0	0.194, 0.775
			1.0	0.775
2.13	2.8	2.8	1.83	0.235 to 0.0991
			0.457 to 1.83	0.737

8.2.1.12 *Flame length for axi-symmetric fire source*

Axi-symmetric fire source — on the floor and away from walls.

Air is entrained from all sides and along the entire height of the plume until the plume becomes submerged in the smoke layer beneath the ceiling.

The height of the flaming region of such a fire is given by:

$$z_{fl} = 0.2Q^{2/5} \qquad (14)\ [15]$$

where

z_{fl} is the mean height of luminous flames above the fuel surface (m)

Q is the total rate of heat release (kW)

This equation is strictly valid only for fires where:

$$z_{fl}/D_s > 3 \qquad (15)$$

where

D_s is the diameter of the source (m)

The correlation indicated by the equation is independent of D_s only for $z_{fl}/D_s > 6$.

For $z_{fl}/D_s < 3$, z_{fl}/D_s is proportional to $Q/D_s^{3/2}$, equation (14) will over-predict flame heights for $z_{fl}/D_s < 3$.

More complex expressions are available for $z_{fl}/D_s < 3$ [see for example Cox, G. and Chitty, R, *Some source dependant effects of unbounded fires* [15] and Heskestad, G., *Luminous heights of turbulent diffusion flame*, Fire Safety Journal vol.5, **103** (1983)], [16] but equation (14) represents an upper limit for the height of the flaming region.

NOTE *Limits*. Equation (14) was originally developed for horizontal-surface fires without substantial in-depth combustion such as liquid pool fires. Experience has shown that many practical fuel sources such as wood pallet fires can be handled by equation (14) (with the exception of very openly constructed pallet stacks). Flame height is then measured from the top surface.

It should be noted that for detection purposes this equation will over-predict the flame height therefore it will not be a conservative estimate for this purpose.

8.2.1.13 *Flame length for line sources*

A line source is a rectangular source where the longer side, d_s is greater than three times the shorter side. For a line source originating on the floor away the walls, the height of the flaming region is given by:

$$z_{fl} = \frac{0.035Q^{2/3}}{(d_s + 0.074Q^{2/5})^{2/3}} \qquad \text{(16) (see DD 240-1)}$$

where

z_{fl} is the mean height of luminous flames above the fuel surface (m)
d_s is the longer linear dimension of the source (m)
Q is the total heat release rate (kW)

However, for rectangular fire sources with the longer side greater than five times the shorter side, the flame length is given by:

$$z_{fl} = \frac{0.035Q^{2/3}}{d_s^{2/3}} \qquad \text{(17) [17,18]}$$

NOTE *Limits*. In practice the equations (16) and (17) may represent a flame that emerges from an open-fronted enclosure fire, horizontal conveyor or cable fires, etc.

8.2.1.14 *Flame lengths for corner room and wall fires*

The presence of walls near the source of a plume can strongly influence the entrainment rate and other properties of the plume. One of the main influences that it can have is that of the flame height.

It should be appreciated that when using a design fire that is in the corner or against a wall of a room, the flame length will increase, compared to the same fire with the same heat release rate in the centre of the room.

Corner room fires are likely to increase flame heights by 75 % and wall fires by 32 %, E.E. Zukoski. [19]

8.2.1.15 *Flame emissivity*

For a luminous flame, the emissivity may be taken as:

$$\varepsilon_f = 1 - \exp(-K\lambda_f) \qquad (18)$$

where

ε_f is the emissivity of the flame
K is the effective emission coefficient (m^{-1})
λ_f is the thickness of the flame (m)

If the flame length $z_{fl} > 1$m and the flame is luminous, it is common to assume black body behaviour and that the emissivity of the flame $\varepsilon_f = 1$.

Table 6 — Effective emission co-efficient, *K*, for various materials

Material	Effective emission coefficient, *K*, m^{-1}
Wood cribs	0.51 [20] – 1.1 [22]
Assorted furniture	1.13 [20]
Diesel oil	0.43 [21]
Polypropylene	1.8 [3]
Polystyrene	5.3 [3]
PMMA	1.3 [3]
Kerosene	2.6 [21]
Petrol	2.0 [21]
Alcohol	0.37 [21]

NOTE *Limits.* Flame emissivity is to be used in calculation procedures for thermal radiation fluxes. It is highly questionable whether alternative approaches are not better suited for the calculations of thermal radiative fluxes.

Calculation of radiative heat fluxes from flames requires as input data flame emissivity, effective values of flame temperature and the flame idealized as a simple geometric shape such as a plane layer or an axi-symmetric cylinder or cone. Calculation procedures may be found in SFPE Handbook of Fire Protection Engineering, Second Edition, 1995, Chapters 1-4 [1]. The simplifying assumptions that are necessary make calculations difficult to use with confidence in practice. A simpler model, based on the assumption that radiation accounts for 20 % to 30 % of total heat release works satisfactorily in many practical cases.

8.2.1.16 *Flame radiation*

The radiant heat flux from a flame depends on a number of factors and is represented as follows:

$$Q_R = \phi \varepsilon_f \sigma \bar{T}^4 \tag{19}$$

where

Q_R radiative heat flux ($W \cdot m^{-2}$)

ϕ configuration factor (geometric relationship between the flame and receiving object)

ε_f emissivity of the flame

σ Stefan-Boltzmann constant (5.67×10^{-11} W/m·K)

$\bar{T}$ mean temperature of the flame (K)

The configuration factor ϕ enables the calculation of radiant intensity at a point remote from the radiator. For the purposes of calculating ϕ, the flame is typically approximated to be a simple geometric shape such as a rectangle or cone. If the flame is influenced by external air flows or fire induced flows, the appropriate configuration factor can be found in McGuire [23], Drysdale [4] and the SFPE Handbook [24].

8.2.1.17 *Smoke mass production rate*

The particulate smoke mass conversion factors for cellulosics and plastic under flaming and non-flaming conditions are given in Mulholland [25]. The mass rate of smoke production can be found from the following equation:

$$m_{part} = \varepsilon_{smoke} m_{fuel} \tag{20}$$

where

m_{part} is the mass rate of smoke particulate production (kg/s)

m_{fuel} is the rate of burning of fuel by mass (kg/s)

ε_{smoke} is the smoke mass conversion factor (kg/kg) — see Table 7.

Table 7 — Smoke mass conversion factors [25]

Material	Smoke conversion factor, ε_{smoke} kg/kg	
	Flaming	Non-flaming
Cellulosics	< 0.01 to 0.025	0.01 to 0.17
Plastics	< 0.01 to 0.17	< 0.01 to 0.19

NOTE *Limits*. The requirement of a well-ventilated fire is emphasized. Below concentration of 12 % to 15 % O_2, smoke yield may increase. Even in the well-ventilated region, smoke yield is dependent on the scenario and the equivalence-ratio.

The upper bound given in Table 7 may be chosen as a suggestion for the design value for free-burning items in the pre-flashover stage and with excess air. Lower values for the smoke conversion factor are allowed only when it can be demonstrated that there is no significant reduction in oxygen concentration in the airflow into the flame.

8.2.1.18 *Optical density of smoke*

Visibility through smoke is often the first thing to hamper occupants making their escape from fire. Light is attenuated by smoke according to the expression:

$$I = I_0 e^{-K_2 s} \tag{21}$$

where

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

K_2 is the extinction coefficient

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

$$I = I_0 10^{-D\mathrm{s}} \tag{22}$$

where

D is the optical density of the smoke per unit path length

($D = 2.3K_2$)

NOTE *Limits*. Equations (21) and (22) are known as Bouguer's law, which is only valid for monochromatic light. However, the equations have been widely used also for polychromatic (white) light, even if a certain deviation might be expected.

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

$$D = \frac{D_m f_b}{V_t} \tag{23}$$

where

D_m is the mass optical density for the fuel concerned ($m^2 \cdot kg^{-1}$)

V_t is the total volume of smoke (m^3)

f_b is the total mass of fuel burnt (kg)

This assumes a homogeneous distribution of smoke throughout the volume of interest.

For the flowing case:

$$D = \frac{D_m m_{fuel}}{V} \tag{24}$$

where

V is the volume flow rate of smoke ($m^3 \cdot s^{-1}$)

m_{fuel} is the mass burning rate of fuel ($kg \cdot s^{-1}$)

8.2.1.19 *Rate of smoke production*

The rate of smoke production RSP is defined as follows:

$$\mathrm{RSP} = cV_f \tag{25}$$

where

RSP is the rate of smoke production ($m \cdot s^{-1}$)

c can be either optical density per metre, D, or extinction coefficient, k, depending on the base used (10 or e)

V_f is the volume flow rate of smoke ($m^3 \cdot s^{-1}$)

Using this, the total smoke production, TSP, can be expressed as:

$$\mathrm{TSP} = \int_0^1 \mathrm{RSP}(t)\mathrm{dt} \tag{26}$$

where

t is the time (s)

More details on smoke measurement units and their derivatives can be found in Östman, B.A [26].

8.2.1.20 *Smoke obscuration*

The optical density of the smoke produced by the combustion products of a specified mass of material in a given volume is given by the following equation: [15]

$$D = 10\left(\frac{D_m f_b}{V_t}\right) \tag{27}$$

where

D is the optical density of the smoke per unit path length (dB/m)

D_m is the mass optical density (m^2/kg)

V_t is the total volume of smoke at a location (m^3)

f_b is the mass of fuel burnt (kg)

Values of D_m for a range of common materials are given in Table 8.

Table 8 — Fire products from well ventilated flaming combustion [25], [2]

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

NOTE *Limits* [12]. Investigations have shown that the correlation between small-scale and large-scale tests breaks down, as the fire becomes complex. In large-scale tests, heat flux and ventilation conditions can have a major impact on smoke production. In a design procedure, a sensitivity analysis is necessary.

8.2.1.21 *Visibility*

$$S = 10/D \qquad (28)\ [27]$$

where

S is the visibility distance (m)
D is the optical density (dB/m)

Where a sign is back illuminated, its visibility distance is increased by a factor of approximately 2.5:

$$S = 25/D \qquad (29)$$

NOTE *Limits* [12]. Equations (28) and (29) do not take account of the irritating effect of smoke on the eyes. For a light extinction coefficient of 0.4 m^{-1} (an optical density per metre of 0.174 m^{-1}), walking speed through irritating smoke is approximately 70 % of that through non-irritating smoke.

Both equations assume that the optical density is known. It is likely that model uncertainty will be smaller than input parameter uncertainty. A sensitivity study is recommended. Alternative information can be found in ANSI/NFP92B Guide for Smoke Management in Malls, Atria and Large Areas. NFPA, Quincy, Massachusetts, 1991 [5].

8.2.1.22 *CO mass production*

8.2.1.22.1 *General*

From the heat release at time *t*, an estimate of the mass rate of carbon monoxide production by a fully ventilated fire at time *t* may be made from the following equation: [25]

$$m_{CO} = 0.013 m_f \qquad (30)$$

where

m_{CO} is the mass rate of carbon monoxide production (kg/s)
m_f is the rate of burning of fuel by mass (kg/s)

NOTE *Limits*. For most design purposes, the mass rate of carbon monoxide and smoke production are proportional to the rate of heat release in a flaming fire and can be determined from equations (20) and (30) respectively; however, this is not necessarily justified for a smouldering or suppressed fire. In these situations, the mass rate of carbon monoxide and smoke production can increase in relation to the rate of heat release.

8.2.1.22.2 *Gas species concentrations*

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

$$c_i = \frac{Y_i f_b}{V_t} \quad (31)$$

where

Y_i is the mass yield of the species i

V_t is the total volume of smoke (m^3)

f_b is the total mass of fuel burnt (kg)

Values of Y_i for carbon monoxide are listed in Table 8 and Table 9.

Table 9 — Fire products from well-ventilated flaming combustion from Tewarson [2] **and Mulholland** [25]

Material	**Carbon monoxide yield,** Y_{CO} (kg/kg)	**Mass optical density,** D_m (m^2/kg)
Plywood	—	290
PMMA	0.010	150
PVC (with plasticizer)	0.063	640
Douglas fir	0.004	280
Polystyrene	0.060	790 to 1 400
Polyurethane	0.024	220 to 330
Ethanol	0.001	—
Kerosene	0.012	—
Benzene	0.067	—
Octane	0.011	—
Silicone	0.006	—

More fuel data are presented in [28]. As for the temperature distribution above, a numerical modelling treatment will be necessary if this assumption is not valid or where more detailed local information is required.

The volume concentration, C_i, is given by:

$$C_i = \frac{c_i}{\rho_i} \quad (32)$$

where

ρ_i is the density of the species i. For CO, ρ is 1.25 kg/m^3.

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

8.2.2 *Fully developed fire*

8.2.2.1 *Heat release rate*

The rate of consumption by mass of fire load is approximately steady over the period of a fully developed fire. During this period, the mass of fire load falls from 80 % to 30 % of its initial value. The steady rate of heat release is given by the following equation:

$$Q_{\mathrm{steady}} = m_{\mathrm{fuel}}\, H_{\mathrm{C}} \tag{33}$$

where

Q_{steady} rate of heat release at steady state (kW)
m_{fuel} mass burning rate of fuel (kg/s)
H_{C} effective calorific value of fire load (kJ/kg)

NOTE *Limits*. This equation assumes complete combustion of the vaporized fuel. In vitiated conditions, there is significant incomplete combustion, particularly for ceiling fires and caution should be taken when applying this equation to calculate heat release rates.

8.2.2.2 *Mass burning rate in ventilation controlled conditions — Method 2* [29]

The ventilation-controlled rate of burning for wood-type fuel in an enclosure may be found from the following equation:

$$m_{\mathrm{f}} = 0.02\sqrt{A_{\mathrm{T}}(w_{\mathrm{c}}/d_{\mathrm{c}})A_{\mathrm{w}}h^{1/2}} \tag{34}$$

where

m_{f} is the ventilation controlled rate of burning by mass ($\mathrm{kg \cdot s^{-1}}$)
A_{T} is $A_{\mathrm{t}} - A_{\mathrm{w}}$, where A_{t} is the total surface area of the enclosure ($\mathrm{m^2}$)
w_{c} is the width of wall containing ventilation openings (m)
d_{c} is the distance front-to-back of the enclosure (m)
A_{w} is the area of ventilation openings ($\mathrm{m^2}$)
h is the height of ventilation openings (m)

This equation has been derived from wood cribs and can be used for most types of fire load found in houses, offices and shops. Conventionally fire load may be expressed in terms of the equivalent weight of wood. If expressed in MJ or in $\mathrm{MJ \cdot m^{-2}}$ the fire load may be converted to kg or $\mathrm{kg \cdot m^{-2}}$ of wood by dividing by the heat of combustion of the particular wood: see Table 10.

Table 10 — Gross heat of combustion values for woods [30]

Wood type	**Gross ΔH_{c}** MJ/kg
Beech	20.2
Birch	20.0
Douglas fir	21.0
Maple	19.1
Red oak	20.2
Spruce	21.8
White pine	19.2
Hardboard	19.9

The gross heat of combustion can be taken as the maximum value of heat of combustion for that product.

NOTE 1 *Limits*. Equation (34) is a refinement of equation (35) allowing for the effect of compartment shape. It is empirical and is based on experiments with wood crib fires, fire loads being not too small and conventional shapes of enclosures. Care has to be taken in using the model for fire compartments with large widths and depths in relation to height of enclosures. The model is not applicable to fires where the fuel load mainly consists of plastics and/or liquid fuels.

A characteristic value of m_{fuel} may be used, as given by the following equation:

$$m_{\mathrm{fuel}} = 0.09 A_{\mathrm{w}}\, h^{1/2} \tag{35}$$

NOTE 2 *Limits*. The equation is not useful as a predictive tool. It describes the stoichiometric burning of wood cribs and is useful as a measure of airflow into a fire compartment.

which is valid for:

$$\frac{\rho_0 g^{1/2} A_{\mathrm{w}} h^{1/2}}{A_{\mathrm{f}}} < 0.24 \tag{36}$$

where

ρ_0 is the density of air at ambient conditions (kg/m^3)
g is the acceleration due to gravity
A_{f} is the total internal floor area of the enclosure (m^2)

8.2.2.3 *Mass burning rate in fuel bed controlled conditions*

The following two methods can be used:

a) *Method 1* [34]

For low values of fire load, the ventilation controlled equation (35) over-estimates the mass rate of burning by a factor of 2 or 3.

With the furnishings typically found in houses, offices and shops, an effective fire duration of 20 min can be assumed and R given by:

$$R = L_{\mathrm{t}}/1\ 200 \tag{37}$$

where

L_{t} is the total fire load (kg) or
R is the mass burning rate (kg·s^{-1})

or

$$L_{\mathrm{t}} = (L_{\mathrm{t}}/A_{\mathrm{f}}) \times A_{\mathrm{f}} \tag{38}$$

where

A_{f} is the floor area (m^2)

Values of (L_t/A_f), kg·m^{-2}, are derived from surveys or design data. Where such data are expressed in MJ·m^{-2} they can be converted by dividing by the heat of combustion of wood, see ventilated controlled fire.

b) *Method 2* [31]

The burning rate of fuel bed controlled fires is difficult to predict. It is to a large extent dependent upon the nature and geometric arrangement of the fuel. Based on work conducted with wood crib fires, the mass loss rate over the area of the fire can be estimated by the following equation:

$$m_{\mathrm{pf}} = 0.0012 M_0 (m_{\mathrm{r}}/M_0)^{1/2} \qquad (39)$$

or the heat release:

$$Q_{\mathrm{pf}} = 0.0158 M_0 (m_{\mathrm{r}}/M_0)^{1/2} \qquad (40)$$

where

m_{pf}	fuel control pyrolysis/mass loss rate (kg·s^{-1})
Q_{pf}	fuel control heat release rate (kW)
M_0	total initial mass (kg) in burnt area
m_{r}	mass remaining (kg) at time t (s) in burnt area

For design purposes, the entire area of the enclosure can be assumed to be fully involved following flashover and m can be evaluated at the point of flashover to determine the peak value of m_{pf}.

In a large space, the fire may not reach flashover and therefore not all of the fuel in the space is ignited where the combustion process, for that system, is at its peak (i.e. fully developed for that system but no flashover). To reasonably predict the effective mass loss rate, the area over which the fuel has ignited should be estimated to determine m and M_0.

The above relationship also takes into account the decay characteristics because m_{pf} reduces with decreasing mass m. In conditions where the fire grows and flashes over relatively quickly, the decay rate is approximately linear. The time to reach burnout following flashover can then be estimated by:

$$t_{\mathrm{bo}} = 2 m_{\mathrm{fo}} / m_{\mathrm{pfo}} \qquad (41)$$

where

m_{fo}	mass remaining at flashover (kg)
m_{pfo}	peak mass loss rate at flashover (kg/s)
t_{bo}	time to reach burnout (s)

8.2.2.4 *Standard temperature-time curve*

Data on the performance of structural elements and fire-resisting separations are normally obtained from tests such as those given in BS 476:Parts 20-22 and ISO 834-1, which utilize a standardized temperature-time curve.

A standard temperature-time curve used to characterize fires in enclosures containing typical cellulosics is given by:

$$\overline{T}_g = 20 + 345\log(8t + 1) \tag{42}$$

where

$\overline{T}_g$ is the mean gas temperature in the enclosure or furnace (°C)
t is the time from ignition (min)

NOTE *Limits*. This is the heating curve for a test furnace and does not describe an enclosure fire. However, the data from tests are particularly useful in establishing the performance of a material or assembly at elevated temperatures.

8.2.2.5 *Hydrocarbon temperature-time curve*

There are two possible methods to determine the hydrocarbon temperature-time curve:

a) *Method 1* (see BS 476-20)

Where the heating regime is considered to equate with a large pool fire (proposed in BS 476-20, Annex D):

$$\Delta T = 1\,100[1 - 0.325\exp(-0.166\,7t) - 0.204\exp(-1.417t) - 0.471\exp(-15.833t)] \tag{43}$$

where

ΔT temperature increase (°C);
t the time at which temperature increase has occurred (min).

b) *Method 2*

A temperature-time curve, in Eurocode 1 (see DD ENV 1991-2-2:1996), designated as the hydrocarbon curve is given by:

$$\overline{T}_f = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + 20 \tag{44}$$

$\overline{T}_f$ is the mean furnace temperature (°C)
t is the time from start of test (min)

8.2.2.6 *Slow heating curve*

The fire resistance of some products determined using the standard temperature–time curve, as specified in BS EN 1363-2:1999 can be substantially reduced in a slowly growing fire. Examples are products that are reactive under the influence of heat. For this reason a slow growing temperature-time curve is proposed.

Where there is an identified requirement for such a fire exposure, the following slow heating curve should be used.

For $0 < t \leq 21$

$$T = 154t^{0.25} + 20 \tag{45}$$

For $t > 21$

$$\overline{T} = 345\log_{10}[8(t - 20) + 1] + 20 \tag{46}$$

where

t is the time from ignition (min)
$\overline{T}$ is the average required furnace temperature (°C)

8.2.2.7 *Maximum temperature-time curve*

The maximum value of enclosure temperature can be used to estimate the impact of a fully developed fire for enclosures bounded by materials having a thermal inertia in the range 720 $\mathrm{J/(m^2 \cdot s^{1/2} \cdot K)}$ to 2 500 $\mathrm{J/(m^2 \cdot s^{1/2} \cdot K)}$. The following equation can be used to determine the maximum expected enclosure temperature [32]:

$$T_{\max} - T_0 = 6000 \frac{1 - \exp(-0.10\eta)}{\eta^{1/2}} \{1 - \exp(-0.05\varphi)\} \tag{47}$$

where

$$\eta = \frac{A_\mathrm{t}}{A_\mathrm{w}(h_\mathrm{w})^{1/2}} \tag{48}$$

$$\varphi = \frac{L}{(A_\mathrm{w} A_\mathrm{T})^{1/2}} \tag{49}$$

$$A_\mathrm{T} = A_\mathrm{t} - A_\mathrm{w} \tag{50}$$

and

$T_{\max}$	is the maximum expected enclosure gas temperature (K)
T_0	is the ambient temperature (K)
A_T	is the area of enclosure surfaces ($\mathrm{m^2}$)
A_t	is the area of enclosure surfaces including area of ventilation opening ($\mathrm{m^2}$)
A_w	is the area of ventilation opening ($\mathrm{m^2}$)
h	is the height of ventilation opening (m)
L_f	is the equivalent fire load of wood (kg)

NOTE *Limits*. The experiments on which equation (47) is based are ventilation controlled, (except for low $A_\mathrm{t}/A_\mathrm{w}h^{1/2}$) and likely to be an upper bound for all fuels which produce given heat output per unit mass of oxygen, i.e. most fuels. The equation is empirical and does not consider thermal properties of wall and ceiling materials.

8.2.2.8 *Ventilation controlled temperature–time curve*

Kawagoe and Sekine [33] describe the temperatures attained in ventilation controlled fires by a parameter, known as an opening factor *F*;

$$F = \frac{A\sqrt{h}}{A_\mathrm{T}} \tag{51}$$

where

A	area of openings in the enclosure ($\mathrm{m^2}$)
h	height of the ventilation openings (m)
A_T	area of bounding surfaces (walls, floor and ceiling) ($\mathrm{m^2}$)
F	opening factor ($\mathrm{m^{1/2}}$)

By solving the heat balance for the enclosure, time-temperature curves could be created. It was found that these temperature curves could be reasonably described by the expression:

$$T = 250(10F)^{0.1/F^{0.3}}\ e^{-F^2 t}\left[3\left(1-e^{-6t}\right)-\left(1-e^{-3t}\right)+4\left(1-e^{-12t}\right)\right]+C\left(\frac{600}{F}\right)^{0.5} \tag{52}$$

where

T is the fire temperature in (°C)
t is the time in (h)
F is the opening factor in ($m^{1/2}$)
C is a constant taking into account the influences of the properties of the boundary material on the temperature.

NOTE *Limits.* $C = 0$ for dense materials ($\rho \geq 1\,600$ kg/m^2) and $C = 1$ for light materials ($\rho < 1\,600$ kg/m^2). The expression is valid for:

$$t \leq \frac{0.08}{F} + 1 \tag{53}$$

and

$$0.01 \leq F \leq 0.15 \tag{54}$$

If $t > (0.08/F)+1$, a value of $t = (0.08/F)+1$ should be used. If $F > 0.15$, a value of $F = 0.15$ should be used.

8.2.2.9 *Heat balance governing equation*

A heat energy balance can be used to determine the temperature-time history for an enclosure. The heat balance is represented by:

$$\dot{Q}_{\text{enc}} = \dot{Q}_{\text{c}} + \dot{Q}_{\text{w}} + \dot{Q}_{\text{r}} + \dot{Q}_{\text{b}} \tag{55}$$

where

$\dot{Q}_{\text{enc}}$ is the rate of heat release in the enclosure (kW)
$\dot{Q}_{\text{c}}$ is the rate of heat loss by convection through openings (kW)
$\dot{Q}_{\text{w}}$ is the rate of heat loss by radiation and conduction through the enclosing construction (kW)
$\dot{Q}_{\text{r}}$ is the rate of heat loss by radiation through openings (kW)
$\dot{Q}_{\text{b}}$ is the rate of accumulation of heat in hot gases in the enclosure (kW)

NOTE *Limits.* This is a definitive fundamental equation. The only reservation is the omission of the heat transfer to the fuel interior. In a steady state, with a constant pyrolysis rate (or evaporation rate), the energy is recovered and only an adjustment to the definition of calorific value is required, but in the early stages of the fire, the interior of the fuel is a heat sink.

Gas temperature/time curves have been derived relating to enclosures having average thermal properties (e.g. brickwork, blockwork, plaster) as a function of fire loading and ventilation. These relationships have been simplified to a group of descriptive equations in DD ENV 1991-2-2:1996.

8.2.3 *Steady burning phase*

The interval between onset of flashover and commencement of decay is termed the duration of steady burning. The duration of steady burning is often characterized as that time interval over which the fire load within the enclosure is reduced from 80 % to 30 % of its initial value.

$$t_{\mathrm{steady}} = \frac{L_{\mathrm{t}}\Delta H_{\mathrm{c}}}{Q_{\mathrm{steady}}} \tag{56}$$

where

t_{steady}	is the duration of steady burning (s)
L_{t}	is the total fire load within the enclosure (kg)
ΔH_{c}	is the heat of combustion of fire load ($\mathrm{kJ \cdot kg^{-1}}$)
Q_{steady}	is the heat release rate during the steady burning phase (kW)

8.2.4 *Decay phase*

When 80 % of the fuel has been consumed the fire can be assumed to decay at a linear rate given by: [33]

$$Q(t) = (1 - 1.75(t - t_{\mathrm{d}})/t_{\mathrm{b}})Q_{\mathrm{max}} \tag{57}$$

where

t_{d}	is the time of onset of the decay phase (s)
t_{b}	is the duration of fully developed burning (s)
Q_{max}	is the heat release rate during the fully developed burning phase (kW)
$Q(t)$	is the heat release rate at time t (kW)
t	is the time from ignition (s)

8.3 Special circumstances

NOTE The list of special circumstances presented in **8.3.1**, **8.3.2** and **8.3.3** is not exhaustive, and other scenarios may need special consideration.

8.3.1 *Malicious fires or arson*

In buildings other than dwellings, the number of malicious fires in the UK has almost doubled over the last ten years to 20 100 [34,35]. These types of fire are often characterized by multiple sources of ignition and/or the use of accelerants such as petrol, white spirit or methylated spirit. Table 11 shows the percentage of all fires that are attributable to malicious fires for a range of building types. Guided by this information and depending upon the type of building, the fire safety engineer should consider the probability of arson occurring and its implications in relation to the choice of the design fire and the overall design approach.

Table 11 — Percentage of all fires that are attributable to malicious fires for a range of building types

Building type	**1997** [34] %	**1998** [35] %
Sheds/garages	72	72
Schools	66	69
Construction	65	59
Agriculture	52	47
All other buildings	42	45
Retail and vehicle	40	44
Hospitals	22	25
Hotel, catering etc.	21	24
Dwellings	20	21
Other industrial	14	17

8.3.2 *Unconfined liquid pool fires*

For some design projects, the liquid fuel spills may be of particular relevance with a significant probability of occurrence. This is likely to be influenced by the location of the building and its use. In such cases, the liquid pool fire itself maybe the design fire. Figure 12 shows the relationship between the steady burning rate and diameter of pool fires. The fire safety engineer should remember that this data is for steady fires and that it will give indicative information about the potential heat release rate. For pool fires that are increasing in diameter as a function of time, a conservative approximation for the heat release rate would be to assume a burning rate of 4 mm/min. Typical values for heats of combustion of hydrocarbon fuels can be found in Table A.20. Heat losses from thin films of liquid fuels are not included in these data.

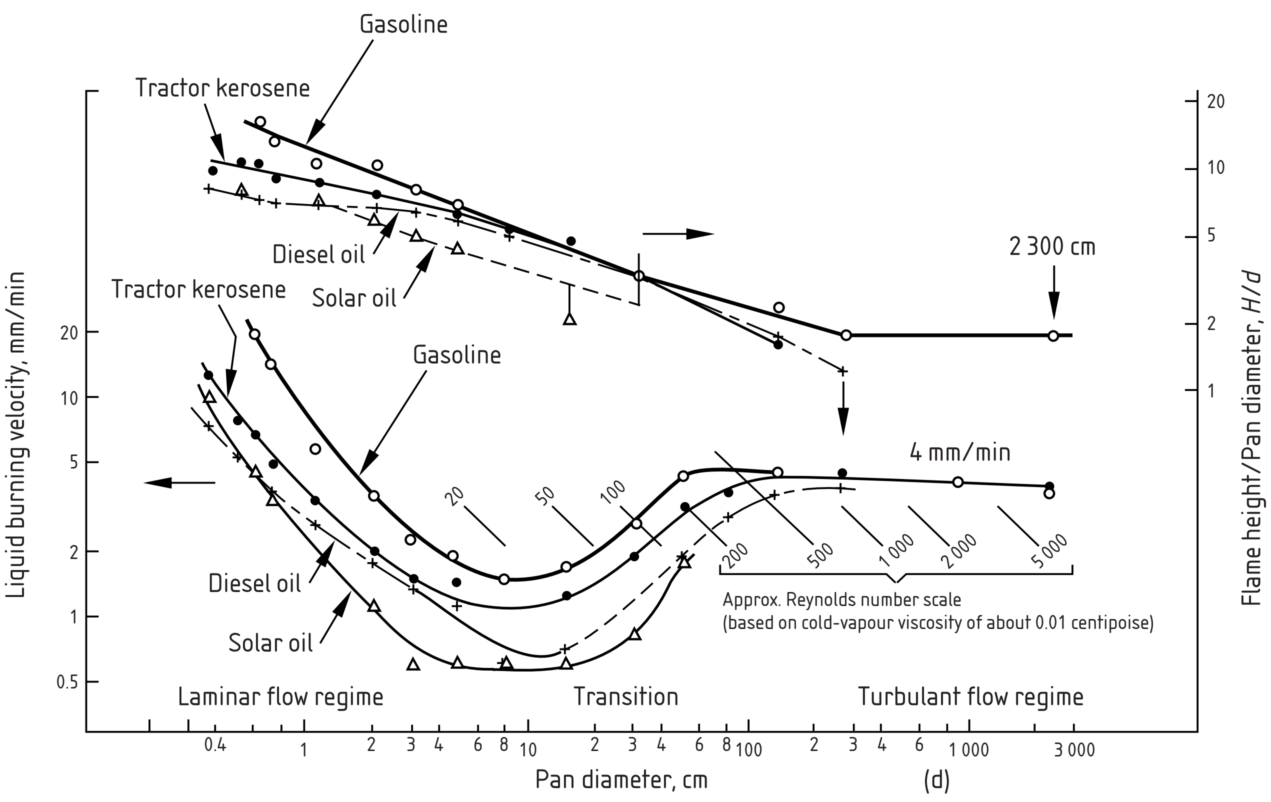


Figure 12 — Burning rate and flame heights for various hydrocarbon pool fires [36]

8.3.3 *Stacked storage of goods and commodities*

Buildings in which the stacked and racked storage of goods and items is a particular feature should be considered carefully. This is because of the potential for rapid vertical flame spread both within and up the exterior of the stacks. The source of ignition can potentially be at any point in the stack and during the QDR, likely sources and locations of ignition should be identified. These will influence the rate at which the fire will grow as well as the flame length, heat release rate (both Q_p and Q^*), entrainment into the fire, smoke layer height, ceiling temperatures and the effectiveness of any active fire protection systems.

There are a number of relevant publications in this area (for example, see [37], [38], [39], [40] and Table A.4.

Annex A (informative) Experimental data

A.1 General

Results from experimental fire test data (including calorimeter data) can be used as a direct source of heat release data for fire models, provided the limitations of the tests are considered and recognized. Most information on burning rates for single items has been reported under free burning conditions. That is, it is representative of items burning in large enclosures. The use of these data can give rise to uncertainties related to free burning conditions because they do not take into account:

a) radiative feedback from the hot smoke layer or from the enclosure surfaces;

b) restriction of the fire by an inadequate supply of oxygen;

c) interaction between objects, due to their location, orientation and storage arrangements.

A.2 Experimental heat release rate data from SFPE handbook of fire protection engineering

NOTE Table A.1, Table A.2, Table A.3 and Table A.4 are taken from SFPE Handbook of Fire Protection Engineering [41].

A.2.1 *Pillows*

The heat release data for pillows is shown in Table A.1.

Table A.1 — Pillows

Filling material	Fabric material	Pillow mass kg	Total mass[a] kg	Peak heat release kW	Total heat release MJ
Latex foam, one piece	50 % cotton / 50 % polyester	1.003	1.238	117	27.5
Polyurethane foam, shredded foam, #1	non-woven	0.650	0.885	43	18.4
Polyurethane foam, shredded foam, #2	non-woven	0.628	0.863	35	18.9
Polyester fibrefill	80 % polyester / 20 % cotton	0.602	0.837	33	10.2
Feathers	Cotton	0.966	1.201	16[b]	8.9
Polyester fibrefill	Fibreglass	0.687	0.922	22	3.1

[a] Includes pillowcase and balled-up newspaper sheets used for ignition

[b] Reading low due to slow ignition; otherwise expect ≃ 20 kW peak

Although the heat release rates of the pillows are low, they can serve as a continued source of heating for a mattress.

A.2.2 *Wardrobes*

Table A.2 shows the heat release rates for wardrobes.

Table A.2 — Wardrobes

Construction	Wardrobe combustible mass kg	Clothing and paper kg	Peak heat release rate kW	Total heat release MJ
Metal	0	3.18[a]	770	70
Metal	0	1.93[b]	270	52
Plywood, 12.7 mm thick, #1	68.5	1.93[b]	3 500	1 067
Plywood, 12.7 mm thick, #2	68.3	1.93[b]	3 100	1 068
Plywood, 3.2 mm thick	36.0	1.93[b]	6 400	590
Plywood, 3.2 mm thick, 1 coat FR paint	37.3	1.93[b]	5 300	486
Plywood, 3.2 mm thick, 2 coats FR paint	37.3	1.93[b]	2 900	408
Particleboard, 19 mm thick	120.3	0.81[b]	1 900	1 349

[a] Miscellaneous rags

[b] Simulated hanging clothes

It was concluded that the peak heat release rate is inversely proportional to the thickness of the wardrobe panels. While the total heat content of the 19 mm particleboard specimen is high, its peak heat release rate is quite low, since the flames spread more slowly over a thick material.

A.2.3 *Television sets*

Table A.3 shows the heat release data for television sets.

Table A.3 — Television sets

Total mass	Combustible mass burned	Peak q kW	Total heat released MJ
32.7	10.2	230	146
27.2	5.8	120	N/A
39.8	10.2	290	150

Data on three "console-type" television sets with wooden cabinets and 24 to 26 inch tube were reported by VTT [42]. These sets were ignited with 100 ml of isopropanol; this ignition source alone constituted a small heat release rate of 4 kW. It can be seen that, with peaks of only 120 kW to 290 kW, these fires were not severe by themselves but could be severe enough to further involve other combustibles in a room.

A.2.4 *Stored commodities*

Table A.4 shows the heat release data for stored commodities.

Table A.4 — Stored commodities

Commodity	Peak heat release rate per unit floor area kW/m^{2}[a]	Growth time to reach 1 MW s
Mail bags, stored 1.5 m high	400 –	190
Cartons, compartmented, 4.9 m high stack	1 700 – 4 200	60
Cartons, tri-wall cardboard, metal lined, 4.9 m stack high	2 800	
Polyethylene bottles, packed in cartons as above	6 200 – 7 600	85
Polyethylene jars, packed in cartons as above	14 000 – 20 900	55
PVC bottles, packed in cartons as above	3 400 – 7 000	95
Polypropylene food tubs, packed in cartons as above	4 400 – 9 600	100
Polyethylene letter trays, stacked 1.5 m high on cart	8 500 –	180
Polyethylene trash barrels in cartons, stacked 4.6 m high	2 000 –	55
Polyethylene bottles, random sized, stacked 4.6 m high	2 000 – 4 200	75
Polyethylene bottles, large, in cartons, stacked 4.6 m high	– 7 300	
Polyethylene/fibreglass shower stalls in cartons, stacked 4.6 m high	1 400 –	85
Polyurethane rigid foam insulation board, stacked 4.6 m high	1 900 – 3 200	8
Polystyrene food tubs, with covers, nested in cartons, stacked 4.3 m high	5 400 – 8 200	120
Polystyrene meat trays, wrapped in plastic sheet	– 12 900	
Polystyrene meat trays, wrapped in paper	– 13 300	
Polystyrene toy parts in cartons, stacked 4.6 m high	2 000 – 6 500	125
Polyethylene and polypropylene film in rolls, stacked 4.3 m high	6 200 –	40

[a] Estimates from Alpert and Ward [43] and Delichatsios [44]

NOTE The spread of values shown refers to the same test in each case, but a different method of estimating the peak heat release rate on the basis of recorded load cell values. In an actual application, the additional variations due to differences in ignition sources and locations, stacking arrangements, and so forth, would have to be considered.

A.3 Christmas tree experimental data

Table A.5, Table A.6 and Table A.7 show the heat release data for artificial and real trees. The information was taken from [45].

Table A.5 — Artificial trees

Test description	Height m	Peak heat release rate kW	Peak mass loss g/s	Peak temp °C	Time from ignition to peak temp s	Duration of burn s
Artificial tree type 1	2.5	100	4.5	465	360	720
Artificial tree type 2	2.0	393	13.5	810	140	360
Artificial tree type 2 with 2.9 kg of mixed decorations	2.1	328	17.6	380	180	480

NOTE 1 Artificial Type 1 — Fire retardant and consisted of a central tubular steel frame from which plastics coated metal wire branches protruded.

NOTE 2 Artificial Type 2 — Not fire retardant and a series of interlocking plastics tubes (forming the main trunk), onto which were fixed radial extending plastics-coated wire branches.

Table A.6 — Real trees undecorated and untreated

Test description	Height m	Peak heat release rate kW	Peak mass loss g/s	Peak temp °C	Time from ignition to peak temp s	Duration of burn s
Large wet Norway spruce	2.79	670	100.7	915	100	150
Large wet Noble fir	3.05	506	88.2	755	98	160
Small dried Norway spruce	1.40	765	49.2	962	39	70
Small dried Noble fir	1.49	1 117	65.9	760	40	85
Medium dried Noble fir	1.83	1 817	104.3	1 050	35	75
Large dried Noble spruce	3.02	1 590	111.1	1 030	60	130
Large dried Noble fir	3.07	2 883	162.7	910	70	100
Large dried Noble fir (flame height test)	3.06	N/A	164.8	N/A	N/A	N/A

Table A.7 — Real trees decorated

Test description	Height m	Peak heat release rate kW	Peak mass loss g/s	Peak temp °C	Time from ignition to peak temp s	Duration of burn s
Real tree – decorated (untreated)						
Large dried Noble fir with 1.9 kg of mixed decorations	2.86	3 321	230.4	1 040	40	110
Real tree – decorated (treated)						
Large dried Noble fir treated with anti-drop spray	2.84	2 736	179.5	910	60	120
Large dried Noble fir treated with fire retardant spray	3.01	N/A	98.1	915	50	160

NOTE 1 Decorations were painted acorns, plastic baubles, paper bows, artificial snow and tree lights.

NOTE 2 The ignition source for these experiments was 150 ml of methylated spirits in a 200 mm-diameter foil dish, located directly under the tree. When ignition did not occur, 250 ml of *n*-heptane was used. In the cases where the samples were easily ignited a gas lighter flame was used.

NOTE 3 This data is for the most commonly used Christmas trees and decorations in the UK. Therefore use of this data for other countries may not be accurate and care should be taken when applying to non-UK scenarios.

A.4 Combustion behaviour of upholstered furniture (CBUF) data

Table A.8 to Table A.17 show the combustion behaviour of upholstered furniture from [46].

Table A.8 — Furniture series 1: Description of commercially available products [46]

Item no	Design	Main filling	Wrap	Cover	Use
1.1	Fully upholstered three seat sofa loose seat and back cushions	Polyester foam seat/polyester interior back	Polyester fibre, seat cushion	100 % Polyester ground cloth /polyacrylic pile	D
1.2	Fully upholstered three seat sofa loose seat and back cushions	CMHR foam seat/shredded foam interior back	N/A	FR treated cotton	D
1.3	As 1.1 but two seat sofa	As 1.1	As 1.1	As 1.1	D
1.4	As 1.2 but single seat chair	As 1.2	As 1.2	As 1.2	D
1.5	Fully upholstered chair loose seat and back cushions	CMHR foam seat/FR polyester interior back	FR polyester fibre	100 % Polyacrylic pile fabric/FR back coated /cellulosic ground	D
1.6	Fully upholstered chair loose seat and back cushions	HR Foam	N/A	Leather	D
1.7	Fully upholstered chair loose seat and back cushions	Polyether foam	Polyester fibre, back cushion	100 % FR cotton	D
1.8	As 1.1 but single seat chair back	As 1.1	As 1.1	As 1.1	D
1.9	Fully upholstered chair loose seat cushion, fixed back	CMHR foam	N/A	FR treated 100 % cotton	D
1.10	Fully upholstered chair loose seat cushion, fixed back	CMHR foam	FR polyester fibre	Polyacrylic pile fibre/FR back coated/cellulosic ground	D
1.11	Fully upholstered chair loose seat cushion, fixed back	HR Foam	N/A	Leather	D
1.12	Fully upholstered chair, loose seat cushion, fixed back	Polyether foam	Polyester fibre	100 % Polyester	D
1.13	Chair-metal frame, seat and back pads mounted on boards (reception/typist)	CMHR foam	N/A	100 % Wool FR treated	C
1.14	As 1.13	CMHR foam	N/A	100 % Wool	C
1.15	As 1.13	Polyether foam	N/A	100 % FR polyester	C
1.16	As 1.14	Polyether foam	N/A	Vinyl coated cover	C
1.17	Executive swivel chair	HR foam	N/A	100 % FR polyester	C
1.18	Executive swivel chair	To meet Cal.T.B.133		100 % Wool tweed	C
1.19	Fully upholstered, fixed upholstery, high arms (reception)	HR foam	N/A	100 % FR polyester	C
1.20	Fully upholstered, fixed upholstery, high arms	CMHR foam	FR polyester fibre, seat	100 % Wool	C
1.21	Solid foam mattress	Polyether foam	FR polyester fibre, quilted to cover	Cotton/viscous	D/C
1.22	Spring foam mattress	Latex foam	N/A	Cotton/viscous	D/C
1.23	Spring interior mattress	Polyether foam	N/A	100 % Polyester	D
1.24	Spring interior mattress	CMHR foam	N/A	100 % Polyester	D
1.25	Solid foam mattress (prison)	Impregnated foam	N/A	FR vinyl reinforced sheet	HR
1.26	Spring interior mattress/sprung edge divan set	Various fibrous (natural) layers		D75 % Polyester 25 % Viscous	D
1.27	As for 1.1, but a sofa bed	As for 1.1	As for 1.1	As for 1.1	D

NOTE D = Domestic, C = Commercial, HR = High risk.

Table A.9 — Furniture series 1 tested in the ISO 9705 room-corner test

Sample identification	Peak heat release rate kW	Time to peak heat release rate s	Total heat release MJ	Total smoke production m^2	Test duration s
1.1[a b]	1 959	152	256.9	7 334	215
1.2[a]	1 714	608	202.9	2 886	616
1.3[a]	2 107	232	357.4	8 119	270
1.4	911	424	405.6	1 906	1 320
1.5	917	480	528.6	5 032	1 800
1.6	1 696	337	353.3	2 040	713
1.7	664	656	354.9	1 466	1 800
1.8	1 570	168	519.2	3 179	1 276
1.9	661	1 240	184.2	1 532	1 800
1.10	1 027	268	431.6	3 425	1 296
1.11[a]	1 849	308	138.1	1 058	311
1.12	1 181	209	200.5	1 262	1 277
1.13	662	1 313	163.3	1 460	1 800
1.14	614	1 157	166.6	1 300	1 800
1.15	1 094	353	267.6	5 459	1 217
1.16	1 035	445	267.2	5 804	1 297
1.17	933	397	331.9	4 554	1 173
1.18	44	121	5.3	146	1 229
1.19	1 430	193	241.3	3 529	1 205
1.20	699	308	106.9	706	1 216
1.21[a]	2 122	187	114.2	1 966	187
1.22[a]	1 599	317	132.6	10 191	332
1.23	414	85	32.9	140	809
1.24	49	121	18.7	93	1 161
1.25	33	122	2.8	43	1 290
1.26	30	121	2.0	7.5	308
1.27[a]	2 363	196	238.7	4 690	220

[a] Data given until the test was extinguished with water, which was before 1 800 s.

[b] THR is adjusted with a factor 1.10, since approximately 10 % of the released energy was lost during the test due to escaping smoke gases from the hood.

Table A.10 — Furniture series 2: Description of "made up" products tested

Item No.	Fabric	Filling	Interliner
2.1	1	1	N/A
2.2	1	3	N/A
2.3	3	1	N/A
2.4	5	1	N/A
2.5	6	1	N/A
2.6	2	1	N/A
2.7	4	1	N/A
2.8	9	1	N/A
2.9	2	1	1
2.10	5	2	4
2.11	1	2	N/A
2.12	1	2	4
2.13	7	4	N/A
2.14	3	3	2
2.15	6	1	3
2.16	2	2	2

All series 2 furniture consists of:

- — loose seat and back cushions, fully upholstered to ground;
- — beach wood timber frame;
- — three seats, with one subdividing arm, and 2 end arms;
- — 760 mm wide × 580 mm depth × 780 mm height.

Table A.11 — Furniture series 2 tested in the ISO 9705 room-corner test

Sample identification	Peak heat release rate kW	Time to 50 kW s	Total heat release MJ	Total smoke production m^2	Test duration s
2.1	832	90	120.4	768	1 295
2.2	850	40	113.4	442	1 245
2.3	1 054	55	214.6	1 217	1 320
2.4	1 176	45	202.5	1 654	1 285
2.5	867	55	172.3	829	1 275
2.6	872	45	117.4	621	1 245
2.7	868	60	171.4	1 316	1 340
2.8	1 325	55	296.7	936	1 250
2.9	887	55	172.1	578	1 260
2.10	1 007	45	203.8	1 674	1 245
2.11	768	105	114.8	668	1 270
2.12	880	85	132.1	836	1 245
2.13	34	N/A	1.0	13	1 245
2.14	712	55	209.1	773	1 845
2.15	43	N/A	3.3	131	1 245
2.16	33	N/A	14.5	39	1 845

Table A.12 — Furniture series 3: Description of "made up" products tested

Item no.	Fabric	Filling	Interliner	Frame	Style	Variation
3.1	1	1	N/A	1	A	Loose seat and back cushions, fully upholstered to the ground
3.2	1	1	N/A	2 (metal)	A	Loose seat and back cushions, fully upholstered to the ground
3.3	1	1	N/A	3	D	Loose seat and back cushions (direct into wooden frame) with arms
3.4	1	1	N/A	3	C	Gap between seat and back panel mounted cushions without arms
3.5	1	1	N/A	1	A	Loose seat and back cushions, 3 seat sofa fully upholstered to ground
3.6	1	1	N/A	3	D	Panel mounted, without arms
3.7	1	1	N/A	3	D	Panel upholstery, without arms
3.8	1	1	N/A	4	E	Panel upholstery, without arms, high back
3.9	1	1	N/A	4	F	Panel upholstered, without arms, high back, buttoned
3.10	1	1	N/A	3	B	Fully upholstered with loose seat and back cushions, show wood legs
3.11	4	1	N/A	1	A	Loose seat and back cushions, fully upholstered to ground
3.12	4	1	N/A	1	A	Loose seat and back cushions, 3 seat sofa, fully upholstered to ground
3.13	4	1	N/A	3	D	Panel mounted, without arms
3.14	4	1	N/A	3	B	Fully upholstered — with loose back cushion, show wood legs
3.15	4	1	N/A	3	D	Panel mounted, with arms
3.16	4	1	N/A	3	C	With reduced foam content in seat and back
3.17	1	1	N/A	N/A	N/A	Solid foam mattress
3.18	1	1	N/A	N/A	N/A	Spring interior mattress

Table A.13 — Furniture series 4: Description of "made up" products tested

Item no.	Fabric	Filling	Interliner	Frame	Style	Variation
4.1	1	1	N/A	1	A	Loose seat and back cushions, fully upholstered to ground
4.2	4	1	N/A	1	A	Loose seat and back cushions, fully upholstered to ground
4.3	5	2	4	1	A	Loose seat and back cushions, fully upholstered to ground
4.4	6	2	N/A	3	B	Two seat sofa, without arms, show wood legs, panel mounted on slats
4.5	8	2	N/A	3	D	Panel mounted, without arms

Table A.14 — Furniture series 4 tested in the large room

Sample identification	Sample mass kg	Mass loss kg	Peak rate of mass loss g/s	Time to peak mass loss s	Heat flux peak at floor level kW·m^{-2}	Heat flux peak at 1.5 m above floor s	Test duration s
4.1	17.401	6.049	40.1	285	1.3	7.8	1 260
4.2	17.052	6.143	28.5	200	0.7	4.3	1 260
4.3	19.304	9.247	52.0	305	1.7	8.3	1 260
4.4	15.769	0.571	4.9	95	<0.1	0.7	1 260
4.5	12.648	0.407	4.1	60	<0.1	0.9	1 135

NOTE Dimensions 7.4 m × 5.7 m × 4.0 m high. The doorway was centrally located in one of the 5.7 m wide walls with dimensions of 2.0 m × 0.8 m.

Table A.15 — Furniture series 1 tested in the furniture calorimeter

Sample identification	Peak heat release rate kW	Total heat release MJ	Total smoke production m^2	Test duration s
1.1	2 154	704.4	5 120	1 456
1.2	1 346	520.4	3 739	1 700
1.3	2 285	658.4	4 572	1 453
1.4	784	368.4	1 752	1 560
1.5	742	463.3	4 926	1 800
1.6	1 158	412.8	1 570	1 472
1.7	596	314.2	1 315	1 800
1.8	1 490	497.6	1 570	1 472
1.9	552	143.6	1 666	1 800
1.10	866	449.0	3 485	1 800
1.11	1 259	374.6	1 244	1 316
1.12	652	171.9	1 307	1 240
1.13	829	156.4	1 347	1 800
1.14	486	150.3	1 178	1 800
1.15	946	261.5	5 658	1 256
1.16	778	245.2	5 061	1 212
1.17	853	303.7	4 063	1 264
1.18	39	13.4	546	1 800
1.19	1 119	224.4	3 751	1 233
1.20	574	104.4	751	1 300
1.21	866	157.5	2 131	1 128
1.22	297	162.0	34 274	1 800
1.23	330	34.2	150	936
1.24	29	17.1	136	1 325
1.25[a]	16	N/A	43	420
1.26[a]	10	N/A	6	600
1.27	1 796	987	6 584	1 800

[a] Very limited burning in item 1.25 and 1.26 after the burner was removed. Almost no mass loss was removed.

Table A.16 — Furniture calorimeter test series 3

Sample identification	Peak heat release rate kW	Total heat release MJ	Total smoke production m^2	Test duration s
3.1	821	175	789	1 331
3.2	697	163	660	1 157
3.3	361	128	597	1 337
3.4	251	129	342	1 323
3.5	1 665	335	1 814	1 340
3.6	262	144	599	1 344
3.7	512	147	736	1 252
3.8	310	163	600	1 331
3.9	313	182	599	1 344
3.10	450	155	677	1 347
3.11	740	219	1 348	1 328
3.12	14.5	437	3 320	1 330
3.13	226	139	547	1 329
3.14	714	157	1 103	1 350
3.15	726	180	1 155	1 329
3.16	167	105	351	1 327
3.17	263	159	1 349	1 636
3.18	40	7	32	921

Samples 2.1, 3.1 and 4.1 were all identical and were tested in all three test scenarios, all other samples were not identical. Table A.17 summarizes the data for identical chairs tested in the ISO 9705 (BS 476-33) room-corner test, furniture calorimeter and large room. The data shows that there is not a significant difference in the burning characteristics of these chairs resulting from the different experimental scenarios, with the exception of the total heat released.

Table A.17 — Scenario comparisons

Test	Sample identification	Peak heat release rate kW	Total heat release MJ	Total smoke production m^2	Test duration s
ISO Room	2.1	832	120.4	768	1 295
Furniture Calorimeter	3.1	821	175	789	1 331
Large room	4.1	854[a]	128[b]	N/M	1 260

[a] This value was not measured but was calculated from the peak rate of mass loss data.

[b] This value was not measured but was calculated from the total mass loss data.

The following information is in the form of calculated estimates only, not experimental data:

a) *Large room peak HRR*

The experimental peak rate of mass loss for this experiment was 40.1 $g \cdot s^{-1}$.

The effective heat of combustion (EHC) obtained from the furniture calorimeter test (sample 3.1) was to calculate the peak heat release rate,

EHC sample 3.1 furniture calorimeter test = 21.3 $MJ \cdot kg^{-1}$

Using

$$Q_p = m_{fuel} H_c = 40.1 \times 21.3 = 854.13\ kW$$

where

Q_p peak heat release rate (kW)

m_{fuel} mass loss rate of fuel ($g \cdot s^{-1}$)

H_c effective heat of combustion ($MJ \cdot kg^{-1}$)

b) *Large room peak THR*

The total experimental mass loss was 6.049 kg.

Using the EHC from the furniture calorimeter test (sample 3.1), the total heat release (THR) can be calculated:

$$THR = m_t \times H_c = 6.049 \times 21.3 = 128.84\ MJ$$

where

THR total heat release rate (MJ)

m_t total mass loss (kg)

H_c effective heat of combustion ($MJ \cdot kg^{-1}$)

A.5 FASTdata

NIST FASTdata [50] is a database of experimental fire test results produced by NIST and is available on CD-ROM. Table A.18 provides a summary of the data that is contained within the June 1999 release.

Table A.18 — Summary of data

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
A							
Acetone (liquid)	Yes	No	No	No	No	Yes	Yes
Aramid (Kevlar) interliner	Yes	No	No	No	No	Yes	Yes
Armchair	No	Yes	No	No	No	Yes	No
B							
Bed	No	Yes	No	Yes	No	Yes	No
Bed/night table	No	Yes	No	Yes	No	Yes	No
Benzene (liquid)	Yes	No	No	No	No	Yes	Yes
Bunk bed	No	No	No	Yes	No	Yes	
C							
Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cellulose	Yes	No	No	No	No	Yes	Yes
Cordura nylon 100 % fabric (CNF)	Yes	No	No	No	No	Yes	Yes
CNF/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
CNF backing coating/aramid (Kevlar) Interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
CNF no backing coating	Yes	No	No	No	No	Yes	Yes
CNF no backing coating/aramid (Kevlar) Interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cotton 100 % fabric	Yes	No	No	No	No	Yes	Yes
Cotton 100 % fabric/aramid (Kevlar) interliner (Glued)/ Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cotton 100 % Fabric/Aramid (Kevlar) Interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cotton 100 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cotton 100 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Cotton 75 %, nylon 25 % fabric	Yes	No	No	No	No	Yes	Yes
Cotton 75 %, nylon 25 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes

Table A.18 — Summary of data *(continued)*

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
F							
Faced rockwool	Yes	No	Yes	No	No	Yes	Yes
Foam mattress	No	No	No	Yes	No	Yes	No
FR particle board	Yes	No	Yes	No	No	Yes	Yes
FR particle board type B1	Yes	No	No	No	No	Yes	Yes
FR Polystyrene	Yes	No	Yes	No	No	Yes	Yes
G							
Gas burner	No	Yes	No	No	No	Yes	No
H							
Heptane (liquid)	Yes	No	No	No	No	Yes	Yes
I							
FR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Isotactic Polypropylene	Yes	No	No	No	No	Yes	Yes
K							
Kiosk	No	No	No	No	Yes	Yes	No
Knitted glass charring fibre	Yes	No	No	No	No	Yes	Yes
Knitted glass charring fibre with FR resin	Yes	No	No	No	No	Yes	Yes
L							
Loveseat	No	Yes	No	No	No	Yes	No
M							
Melamine faced high density non-combust board	Yes	Yes	No	No	No	Yes	Yes
Methanol (liquid)	Yes	No	No	No	No	Yes	Yes
Methyl methacrylate (liquid)	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, nylon 25 % fabric	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, nylon 25 % fabric/aramid (Kevlar) interliner	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, nylon 25 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, Nylon 25 % Fabric/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, nylon 25 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Modacrylic 75 %, nylon 25 % fabric/knitted glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes

Table A.18 — Summary of data *(continued)*

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
N							
Natural gas	No	Yes	No	No	No	Yes	No
Night table	No	Yes	No	No	Yes	Yes	No
Nylon 100 % fabric	Yes	No	No	No	No	Yes	Yes
Nylon 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Nylon 100 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Nylon 100 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
O							
Ordinary Plywood	Yes	No	Yes	No	No	Yes	Yes
P							
Painted gypsum paper plaster board	Yes	No	Yes	No	No	Yes	Yes
Phenolic resin (Novalac)	Yes	No	No	No	No	Yes	Yes
Phenolic resin (Resole)	Yes	No	No	No	No	Yes	Yes
Plastic faced steel sheet on min wool	Yes	No	Yes	No	No	Yes	Yes
PMMA	Yes	No	No	No	No	Yes	Yes
Polyester 100 % fabric	Yes	No	No	No	No	Yes	Yes
Polyester 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 100 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 100 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 37 %, Cordura nylon 63 % fabric	Yes	No	No	No	No	Yes	Yes
Polyester 37 %, Cordura nylon 63 % fabric/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 38 %, cotton 62 % fabric	Yes	No	No	No	No	Yes	Yes
Polyester 38 %, cotton 62 % fabric/aramid (Kevlar) interliner /Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 38 %, cotton 62 % fabric/ Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes

Table A.18 — Summary of data *(continued)*

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
Polyester 38 %, Cotton 62 % Fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyester 38 %, cotton 62 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polyethylene 60 %, Polypropylene 40 %	Yes	No	No	No	No	Yes	Yes
Polypropylene	Yes	No	No	No	No	Yes	Yes
Polypropylene (liquid)	Yes	No	No	No	No	Yes	Yes
Polypropylene 100 % fabric	Yes	No	No	No	No	Yes	Yes
Polypropylene 100 % fabric/aramid (Kevlar) interliner	Yes	No	No	No	No	Yes	Yes
Polypropylene 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, Heavy 100 % Fabric	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/aramid (Kevlar) interliner/IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/knitted glass charring fibre/IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/knitted glass charring fibre with FR resin/IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, heavy 100 % fabric/woven glass fibre/IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes

Table A.18 — Summary of data *(continued)*

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
Polypropylene, light 100 % fabric	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/aramid (Kevlar) interliner/ IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/knitted glass charring fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/knitted glass charring fibre/ IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/woven glass fibre/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Polypropylene, light 100 % fabric/woven glass fibre/IFR Polyurethane with melamine	Yes	No	No	No	No	Yes	Yes
Polystyrene	Yes	No	No	No	No	Yes	Yes
Polystyrene disk (7.3 cm diameter)	Yes	No	No	No	No	Yes	Yes
Polyurethane foam covered with steel sheets	Yes	No	Yes	No	No	Yes	Yes
Polyvinyl alcohol (liquid)	Yes	No	No	No	No	Yes	Yes
PVC wall carpet on gypsum board	Yes	No	Yes	No	No	Yes	Yes
S							
Siloxane 344 (liquid)	Yes	No	No	No	No	Yes	Yes
Styrene (liquid)	Yes	No	No	No	No	Yes	Yes
T							
Textile wall covering on gypsum board	Yes	No	Yes	No	No	Yes	Yes
Toluene (liquid)	Yes	No	No	No	No	Yes	Yes
V							
Veneer particle Board	Yes	No	No	No	No	Yes	Yes
Vinyl 100 % fabric	Yes	No	No	No	No	Yes	Yes
Vinyl 100 % fabric/aramid (Kevlar) interliner/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Vinyl 100 % fabric/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes

Table A.18 — Summary of data *(continued)*

Product	Cone calorimeter	Non standard room test	Corner room test	Free burn in open space	Multi-storey building	Time history graph summary	Tabulated data summary
W							
Wood crib	No	No	No	No	Yes	Yes	No
Wood dresser	No	No	No	Yes	No	Yes	No
Wood pallet	No	No	No	Yes	No	Yes	No
Wool 30 %, cotton 60 %, rayon 6 %, 4 % nylon fabric	Yes	No	No	No	No	Yes	Yes
Wool 30 %, cotton 60 %, rayon 6 %, 4 % nylon fabric/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric (glued corners)	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric (glued corners) aramid (Kevlar) interliner/ Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric (glued corners)/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric/aramid (Kevlar) interliner/ Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Wool 32 %, cotton 60 %, nylon 8 % fabric/Cal 117 Polyurethane	Yes	No	No	No	No	Yes	Yes
Woven glass fibre	Yes	No	No	No	No	Yes	Yes

A.6 Survey of shops

An investigation of over 90 shops around England, Wales and Scotland was carried out by Piers [47] and summarized by Hume [48]. The results of the survey drew particular attention to materials likely to support rapid fire growth. This included the following:

- toys in blister packs, on hanging arms against the wall;
- tights in cartons, on hanging arms against the wall;
- soft toys, arranged in a large pile;
- video cassettes displayed on either a plastic rack or metal shelves;
- crisps displayed on open wire mesh shelving;
- lightweight sports jackets on metal hanging arms against the wall.

These conclusions were made after small scale testing had been applied to a selected range of products.

For further information and small-scale data from the research and survey; see Piers [47].

Care should be taken in extrapolating small-scale results to full scale.

A.7 Unsprinklered and sprinklered design fires

A series of experiments have been carried out by FRS [49], [51] and [53] to provide a database of the characteristics of fires for use in design of fire protection and life safety systems in buildings.

The experiments were large-scale fire tests on realistic fire loads. They were carried out unsprinklered and then repeated to establish a direct comparison in relation to the potential effect of sprinklers. Measurements were made of:

- heat release rate;
- mass flow rate;
- smoke production rate;
- gas temperatures;
- radiant and total heat fluxes;
- CO and CO_2 production rates.

Results for tests on the following fire loads are reported:

- soft toy “mountain”;
- idle wooden pallet array;
- simply stacked cardboard boxes containing polystyrene packaging;
- retail sports clothing;
- open plan office;
- office reception area (10 m^2 loading);
- retail carpet store;
- retail handcart;
- soft play area;
- retail luggage display;
- nightclub/theme bar.

Further information can be found in:

- Reference [50], NIST FASTdata;
- Reference [52] on expected size of shielded fires in sprinklered office buildings; and
- Reference [54] on office workstation heat release rate study: full scale versus bench scale.

A.8 Fire load densities in different occupancies

Table A.19 shows the fire load densities in various occupancies.

Table A.19 — Fire load densities

Occupancy	**Fire load density**[a]			
	Average MJ/m^2	**Fractile**[b] MJ/m^2		
		80 %	**90 %**	**95 %**
Dwelling	780	870	920	970
Hospital	230	350	440	520
Hospital Storage	2 000	3 000	3 700	4 400
Hotel bedroom	310	400	460	510
Offices	420	570	670	760
Shops	600	900	1 100	1 300
Manufacturing	300	470	590	720
Manufacturing and storage[c]	1 180	1 800	2 240	2 690
Libraries	1 500	2 250	2 550	—
Schools	285	360	410	450

NOTE 1 *Limits*. The fire load densities given in this table assume perfect combustion, but in real fires, the heat of combustion is usually considerably less.

NOTE 2 The values given in this table included only the variable fire loads (i.e. building contents). If significant quantities of combustible materials are used in the building construction, this should be added to the variable fire load to give the total fire load.

[a] Derived from surveys: see CIB W14 Workshop Report, 1983 [1].

[b] The 80 % fractile is the value that is not exceeded in 80 % of the rooms or occupancies.

[c] Storage of combustible materials at less than 150 kg/m^2.

A.9 Calorific values of common fuels

Table A.20 shows the calorific values of common fuels.

Table A.20 — Calorific values of common fuels

	Material	Calorific value MJ/kg
Solid	Anthracite	34
	Asphalt	41
	Bitumen	42
	Cellulose	17
	Charcoal	35
	Coal, coke	31
	Cork	29
	Cotton	18
	Grease	41
	Kitchen refuse	18
	Leather	19
	Linoleum	20
	Paper, cardboard	17
	Paraffin wax	47
	Foam rubber	37
	Rubber isoprene	45
	Rubber tyre	32
	Silk	19
	Straw	16
	Wood	18
	Wool	23
Liquids	Particle board	18
	Gasoline (petrol)	44
	Diesel oil	41
	Linseed oil	39
	Methanol	20
	Paraffin (kerosene)	41
	Spirits	29
Plastics	Acrylonitrile butadiene styrene (ABS)	36
	Polymethyl methacrylate (PMMA)	28
	Celluloid	19
	Epoxy	34
	Melamine resin	18
	Phenol formaldehyde	29
	Polyester	31
	Polyester, glass-fibre-reinforced	21
	Polyethylene	44
	Polystyrene	40
	Polyisocyanurate foam	24
	Polycarbonate	29
	Polypropylene	43
	Polyurethane	23
	Polyurethane foam	26
	Polyvinyl chloride	17
	Urea formaldehyde	15
	Urea formaldehyde foam	14

blank

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