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Fire safety engineering —

Part 4:
Initiation and development of fire and generation of fire effluents

Ingénierie de la sécurité contre l'incendie —

Partie 4: Amorçage et développement des feux et production des effluents du feu

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of ISO technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard (“state of the art“, for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 13387-4, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92*, Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

It is one of eight parts which outlines important aspects which need to be considered in making a fundamental approach to the provision of fire safety in buildings. The approach ignores any constraints which might apply as a consequence of regulations or codes; following the approach will not, therefore, necessarily mean compliance with national regulations.

ISO/TR 13387 consists of the following parts, under the general title *Fire safety engineering:*

— *Part 1: Application of fire performance concepts to design objectives*

— *Part 2: Design fire scenarios and design fires*

— *Part 3: Assessment and verification of mathematical fire models*

— *Part 4: Initiation and development of fire and generation of fire effluents*

— *Part 5: Movement of fire effluents*

— *Part 6: Structural response and fire spread beyond the enclosure of origin*

— *Part 7: Detection, activation and suppression*

— *Part 8: Life safety — Occupant behaviour, location and condition*

Annex A of this part of ISO/TR 13387 is for information only.

Introduction

Evaluation of the initiation and development of fire and the generation of smoke and toxic species is an essential step in the fire safety design of buildings, processes, etc. These phenomena have been actively studied especially during the last twenty years. Calculation methods and computer codes have been developed to make the necessary evaluations. At the same time, advances in experimental techniques have made it possible to produce input data for the calculation methods and to run large-scale tests for assessing the validity and limitations of the models.

In most of the existing fire safety regulations, measures are taken to prevent the ignition of a fire by controlling the use of materials and by controlling the amount and location of possible ignition sources. It is not, however, possible to prevent all ignitions, and therefore measures are taken to control the fire development and the generation of smoke and toxic species. In most of the existing building regulations, ignitability, flame spread, burning rate, smoke production and toxic-species production are controlled by what are known as reaction-to-fire and flammability classifications. These are to a great extent empirical and based on product performance in a specific small-scale test. Similar regulations have been set on building contents, e.g. upholstered furniture, stored goods, etc., in some countries.

A more modern approach for prescriptive regulations is to establish the classification scheme based on small-scale tests in such a fashion that relative performance in one or more full-scale fire scenarios is replicated. If the scenarios are sufficiently representative of real fire scenarios, the classification system becomes more reliable than those based on performance in small-scale tests alone.

In this document, the initiation and development of fire and the generation of hazardous species is considered as part of a global fire safety evaluation system. This part of ISO/TR 13387 is intended for use together with the other parts as described in clause 6. For some applications, this part alone may be sufficient.

Clause 6 of this part of ISO/TR 13387 describes and provides guidance on the methods available to describe the physical and chemical processes involved in:

- initiation of fire;
- fire development;
- smoke generation;
- toxic-species generation.

Clause 7 is a discussion of the engineering methods available to evaluate the initiation and development of fire and the generation of smoke and gaseous species.

Quantitative information may be related to specific test conditions and/or specific commercial products, and thus the application of data under different conditions may result in significant errors.

Fire safety engineering —

Part 4:
Initiation and development of fire and generation of fire effluents

1 Scope

This part of ISO/TR 13387 is intended to provide guidance to designers, regulators and fire safety professionals on the use of engineering methods for the prediction of the initiation of fire, the generation of fire effluents and the development of fire inside the room of origin. It is not intended as a detailed design guide, but could be used as the basis for the development of such a guide.

This part of ISO/TR 13387 provides a framework for critically reviewing the suitability of an engineering method for assessing the potential for the initiation and development of fire and the generation of fire effluents. It also provides guidance on the means to assess the effectiveness of fire safety measures meant to reduce the probability of ignition, to control fire development and to reduce the accumulation of heat, smoke and toxic products or products causing non-thermal damage. The methods for calculating the effects of design fires for use in the design and assessment of fire safety of a building are also addressed.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO/TR 13387. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO/TR 13387 are encouraged to investigate the possibility of applying the most recent additions of the normative documents indicated below. For undated references, the latest addition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid international standards.

ISO 31-0:1992, *Quantities and units — Part 0: General principles.*

ISO 1000:1992, *SI units and recommendations for the use of their multiples and certain other units.*

ISO 5660-1:1993, *Fire tests — Reaction to fire — Part 1: Rate of heat release from building products — (Cone calorimeter method).*

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions.*

ISO 9705:1993, *Fire tests — Full-scale room test for surface products.*

ISO/TR 11696-1, *Use of reaction to fire tests — Part 1: Application of results to predict fire performance of building products by mathematical modelling.*

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

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

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

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

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

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

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

ISO 13571, *Fire hazard analysis — Life-threatening components of fire.*

ISO 13943, *Fire safety — Vocabulary*.

3 Terms and definitions

For the purposes of this part of ISO/TR 13387, the terms and definitions given in ISO 13943 and ISO/TR 13387-1 and the following apply.

3.1
emissivity
the ratio of the power per unit area radiated from a surface to that radiated from a black body at the same temperature

3.2
extinction coefficient
a constant determining the decay of the light intensity in smoke per unit path length, given by $K = (1/l) \ln (I_0/I)$

It is expressed in m^{-1}.

3.3
fire exposure
a process by which, or the extent to which, humans, animals, materials, products or assemblies are subjected to the conditions created by a fire

3.4
heat flux
the rate at which heat crosses a surface per unit area of surface, expressed in W/m^2

In ISO 1000 and ISO 31-0, this is referred to as "density of heat flow rate".

3.5
heat of combustion
the energy which unit mass of material or product is capable of releasing by complete combustion, expressed in J/kg

3.6
heat of gasification
the quantity of energy required to change a unit mass of material from condensed phase to vapour without change of temperature, expressed in J/kg

3.7
ignition temperature
the minimum temperature measured on a material at which sustained combustion can be initiated under specific test conditions, expressed in K

3.8
opening factor
$A_\text{V}(h_\text{V})^{1/2}/A_\text{T}$

It is expressed in $m^{1/2}$.

For the meanings of the symbols, see clause 4.

3.9
pyrolysis
a process of simultaneous phase and chemical-species change caused by heat

3.10
smoke point
minimum height of a laminar axisymmetric diffusion flame (fuel volumetric mass loss rate) at which smoke escapes from the tip of a flame, expressed in m

3.11
specific heat capacity
heat capacity divided by mass, expressed in J/(kg·K)

3.12
thermal conductivity
ratio of heat flux to temperature gradient, defined by the relation $\vec{q}'' = -k \times \nabla T$

It is expressed in W/(m·K).

3.13
thermal diffusivity
κ
thermal conductivity divided by the density and the specific heat capacity, given by $\kappa = k/\rho c$

It is expressed in m^2/s.

3.14
thermal inertia
the product of the thermal conductivity, the density and the specific heat capacity, given by $k\rho c$

It is equal to the square of thermal effusivity as defined in ISO 7345. It is expressed in $J^2/(m^4 \cdot K^2 \cdot s)$.

3.15
total cross-sectional area of smoke
the average cross-sectional area of smoke particles perpendicular to the light path multiplied by the number of smoke particles, expressed in m^2

3.16
ventilation factor
$A_\mathrm{v}(h_\mathrm{v})^{1/2}$

It is expressed in $m^{5/2}$.

For the meanings of the symbols, see clause 4.

4 Symbols and abbreviated terms

A_v	area of an opening, expressed in m^2
A_fuel	surface area of fuel, expressed in m^2
A_F	floor area, expressed in m^2
A_T	total area of the bounding surfaces in an enclosure, expressed in m^2

α	$\dot{Q}_0 t_{\mathrm{g}}^{-2}$, expressed in W·s^{-2}
F_0	opening factor, expressed in m$^{1/2}$
F_{V}	ventilation factor, expressed in m$^{5/2}$
f_X	yield of species X, where X = CO, CO$_2$, etc.
g	acceleration due to gravity, expressed in m/s^2
h_{v}	height of an opening, expressed in m
I	intensity of light after passing through smoke, expressed in W/m^2
I_0	intensity of light in clean air, expressed in W/m^2
k	thermal conductivity, expressed in W/(m·K)
K	extinction coefficient, expressed in m^{-1}
κ	thermal diffusivity, expressed in W/(m·K)
l	optical path length, expressed in m
L	thickness of a specimen, expressed in m
m	smoke density, expressed in dB/m
$\dot{m}_{\mathrm{fuel}}$	mass loss rate of fuel, expressed in kg/s
$\dot{m}_X$	generation rate of species X, where X = CO, CO$_2$, etc., expressed in kg/s
N	total number of smoke particles
n	number density of smoke particles, expressed in m^{-3}
ϕ	fuel to air equivalence ratio
$\dot{Q}$	heat release rate, expressed in W
$\dot{Q}_0$	heat release rate at the growth time in t^2 fires, expressed in W; usually taken as 1 MW
$\vec{q}''$	heat flux (density of heat flow rate), expressed in W/m^2
$\dot{q}''_{\mathrm{ext}}$	external heat flux, expressed in W/m^2
$\dot{q}''_{\mathrm{loss}}$	heat loss from the surface by convection or radiation, expressed in W/m^2
ρ	density, expressed in kg/m^3
σ	effective absorption cross-section of a smoke particle, expressed in m^2
T	temperature, expressed in °C
T_{ig}	ignition temperature, expressed in °C
T_{L}	the lowest temperature at which a flammable mixture at its lean limit may burn, expressed in °C
T_0	initial surface temperature, expressed in °C

T_U	the lowest temperature at which a flammable mixture at its rich limit may burn, expressed in °C
t	time, expressed in s
t_g	growth time in a t^2 fire, expressed in s
t_ig	time to ignition (ignition delay), expressed in s
τ	time constant, expressed in s
$\dot{V}_\mathrm{f}$	volume flow rate, expressed in m^3/s
V_X	volumetric production rate of species X, where X = CO, CO_2, etc., expressed in m^3/s
x_f	flame height, expressed in m
x_p	position of pyrolysis front, expressed in m

5 Subsystem 1 of the total design system

The approach adopted in the work of ISO/TC 92/SC 4 is to consider the global objective of fire safety design. The global design, described in more detail in ISO/TR 13387-1, is sub-divided into what are called "subsystems" of the total design. A key principle is that inter-relation and interdependence of the various subsystems are appreciated, and that the consequences of all the events in any one subsystem on all other subsystems are identified and addressed. Another key principle is that the design is time-based to reflect the fact that real fires vary in severity and extent with time. Ignition represents zero time.

In ISO/TR 13387-1, the total fire safety design is illustrated by an information bus analogy. The information bus has three layers: global information, evaluation information and process information. In this information bus analogy, subsystem 1 (SS1) concerns the initiation and development of fire and generation of fire effluent and is illustrated in Figure 1. SS1 draws on other subsystems for the prescription or characterization of a fire and, in turn, provides information for the other subsystems to employ. Definitions of terms concerning the global information bus are given in ISO/TR 13387-1.

For example, SS1 provides the information on heat, smoke and species generation, which is then used by SS2 for the calculation of smoke movement out of the room and in the building and by SS5 to assess evacuation and rescue provisions. SS1 also calculates the temperature history in the enclosure of fire origin, which then is employed by SS3 to predict the structural behaviour. The temperature and flow profiles in the room are employed by SS4 to predict the detection of fire, as well as the activation of smoke control and suppression systems. The time of activation of active control systems is then fed back by SS4 to SS1 for the prediction of subsequent fire development and smoke and species generation. The initiation of a fire and its development outside the enclosure of origin are also calculated by SS1.

The evaluations, and processes needed to do the evaluations, are discussed in detail in clause 6.

6 Subsystem 1 evaluations

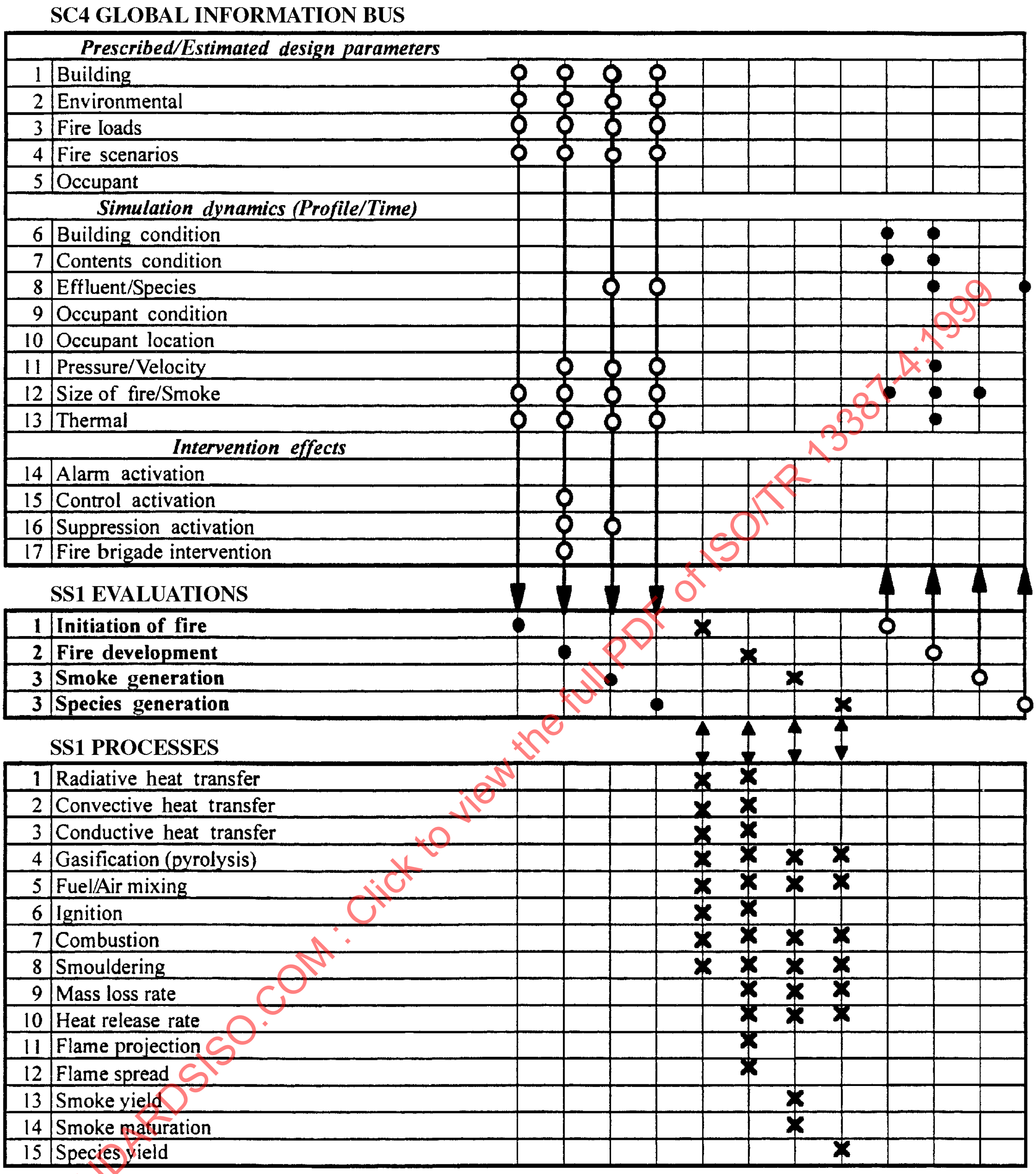
6.1 General

In this clause, various fire phenomena and consequences of fire will be discussed. The required input information and the possible output information will be identified. Areas for which shortages in engineering methods and lack of knowledge are known to exist will be addressed. The text makes reference to existing acknowledged literature, whenever such is available.

6.2 Initiation of fire

6.2.1 Evaluation of initiation of fire

In deterministic fire safety engineering design, ignition is often simply assumed to occur and no calculations on the ignition process are performed. In other instances, especially when the combustible contents and the distribution of ignition sources in the room of fire origin are known, performing calculations on the ignition process can provide valuable information on the possible fire development in the room. Evaluation of ignition is needed especially when the fire safety engineer has to evaluate whether one product can be replaced by another, all other design parameters being fixed. Often the task is to consider if a potential ignition source is likely to cause ignition of adjacent items, i.e. if the first item ignited will cause a second item to be ignited, and thereby the fire to spread to a hazardous extent.



SC4 GLOBAL INFORMATION BUS

	Prescribed/Estimated design parameters												
1	Building	○	○	○	○								
2	Environmental	○	○	○	○								
3	Fire loads	○	○	○	○								
4	Fire scenarios	○	○	○	○								
5	Occupant												
	Simulation dynamics (Profile/Time)												
6	Building condition									●	●		
7	Contents condition									●	●		
8	Effluent/Species			○	○						●		●
9	Occupant condition												
10	Occupant location												
11	Pressure/Velocity		○	○	○						●		
12	Size of fire/Smoke	○	○	○	○					●	●	●	
13	Thermal	○	○	○	○						●		
	Intervention effects												
14	Alarm activation												
15	Control activation		○										
16	Suppression activation		○	○									
17	Fire brigade intervention		○										

SS1 EVALUATIONS

1	**Initiation of fire**	●				✖				○			
2	**Fire development**		●				✖				○		
3	**Smoke generation**			●				✖				○	
3	**Species generation**				●				✖				○

SS1 PROCESSES

1	Radiative heat transfer					✖	✖						
2	Convective heat transfer					✖	✖						
3	Conductive heat transfer					✖	✖						
4	Gasification (pyrolysis)					✖	✖	✖	✖				
5	Fuel/Air mixing					✖	✖	✖	✖				
6	Ignition					✖	✖						
7	Combustion					✖	✖	✖	✖				
8	Smouldering					✖	✖	✖	✖				
9	Mass loss rate						✖	✖	✖				
10	Heat release rate						✖	✖	✖				
11	Flame projection						✖						
12	Flame spread						✖						
13	Smoke yield							✖					
14	Smoke maturation							✖					
15	Species yield								✖				

Bus connection key

● = Input data

○ = Output data

✖ = Subsystem bus data exchange

Figure 1 — Illustration of the global information, evaluation and process buses for SS1

The probability of ignition is a subset of design fires which is addressed in ISO/TR 13387-2. Assessment of the probability of ignition is needed when making decisions about the design fire scenarios and event trees used in risk assessment. Probabilistic design and risk assessment are discussed in more detail in ISO/TR 13387-1.

This subclause discusses ignition of items which are in one way or another exposed to heating from an external source. This source of heat can be of various intensities and shapes, varying from (say) a match flame to an actively burning fuel package. Fire development as discussed in 6.3 can be considered to be a series of non-simultaneous ignitions, each of which generally behaves in the theoretical manner discussed herein.

Figure 2 identifies parameters having an influence on the ignition of various kinds of fuel. A condition for ignition is that both a flammable substance and an ignition source exist. The flammable substance may appear in a number of different forms. The heat transfer from the ignition source to the flammable substance may also take different forms, the processes being, in addition, sensitive to the local environment around the source and the exposed substance.

6.2.1.1 Input

The evaluation of the initiation of a fire (see Figure 1) requires as input information from the global information the following:

- building parameters (e.g. lining materials, their thermal and chemical properties, their location with respect to heat sources);
- fire loads (building contents, thermal and chemical properties of building contents, location with respect to heat sources);
- fire scenarios (properties of ignition sources, their number and their locations);
- thermal profile (radiative, conductive and convective heat fluxes, gas temperature, initial fuel temperature);
- size of fire/extent of smoke (area exposed to a burning fire).

NOTE This information is also needed for evaluating the ignition of second, etc., items. Therefore, e.g. the size of fire/extent of smoke is an input or output, depending on when it is used during an evaluation.

6.2.1.2 Output

The evaluation of the initiation of a fire (see Figure 1) provides the following information to the global information:

- fire scenarios (object first ignited, time to ignition);
- size of fire/ extent of smoke (area first ignited, size of initial flame).

6.2.2 Gas phase ignition

The process of ignition to give flames requires mixtures of gas phase combustibles at an appropriate fuel-to-air ratio and either local temperature fields higher than the auto-ignition limit or a pilot source. The necessary conditions for any gaseous mixture of fuel are usually expressed as ignitability regions as in Figure 3. If a fuel is not naturally in the gas phase, energy must be applied to the substance to bring it to the gaseous state. For liquids, the amount of energy required depends on the vaporisation rate and the way in which the liquid is distributed or the material upon which the liquid is absorbed, i.e. bulk liquids will not ignite until the bulk temperature equals or exceeds the flash point. If the liquid is atomised, its ignition propensity will approach the ignitability of gaseous mixtures of the same material, depending on the degree of atomisation and the temperature of the environment. If the liquid is absorbed in a porous medium, the energy demand for ignition will depend on how fast the porous material will absorb energy and heat up. In this case, the thermal properties of the porous medium will dominate the process.

In the case of gaseous or liquid fuels, the engineering task is usually to consider whether a flammable mixture can be created in the space of concern. In the case of solids, the task can usually be reduced to evaluating whether the surface temperature will become high enough to cause ignition, and no gas phase considerations are needed as we can see in 6.2.3.

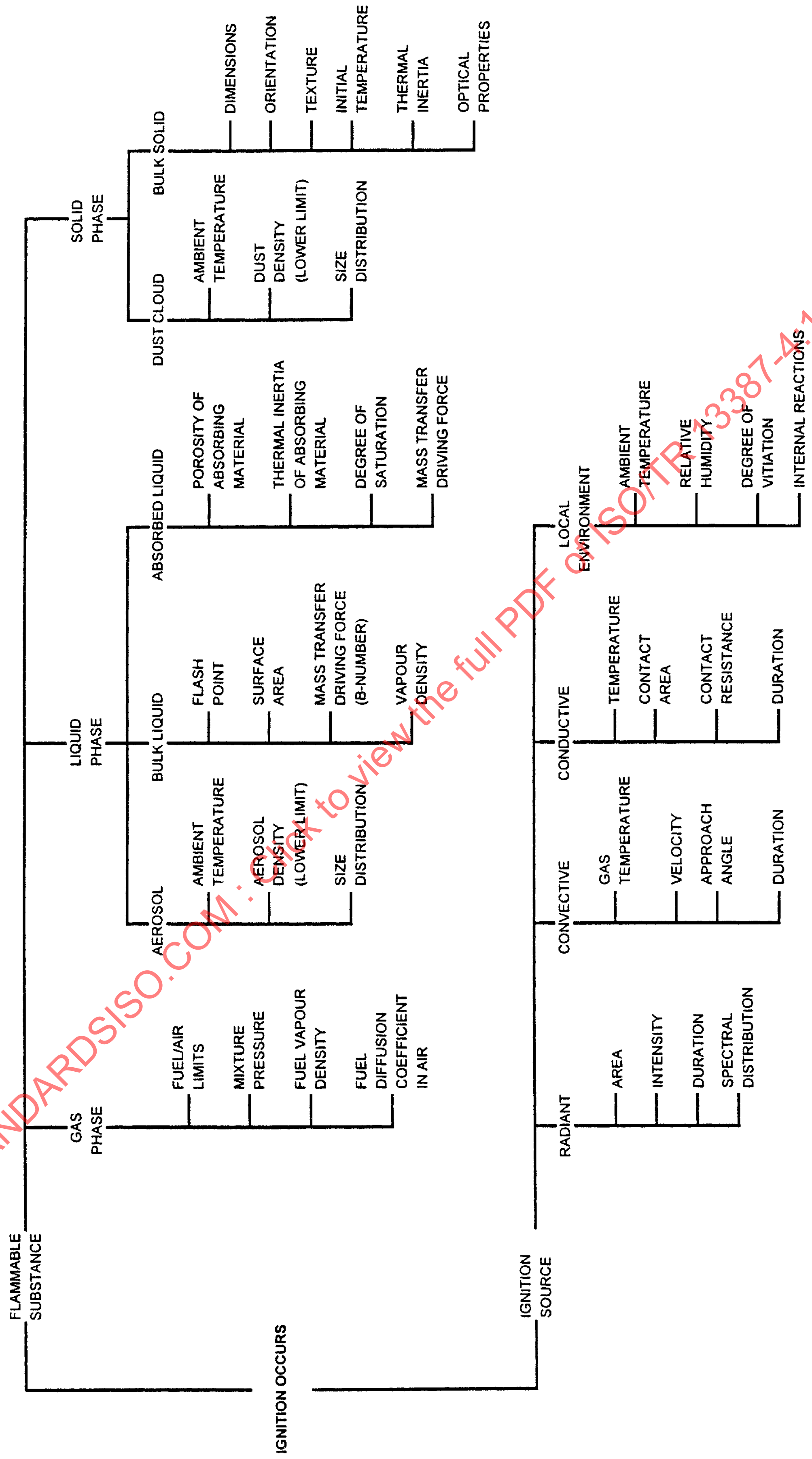


Figure 2 — Factors to be taken into account when assessing ignition potential

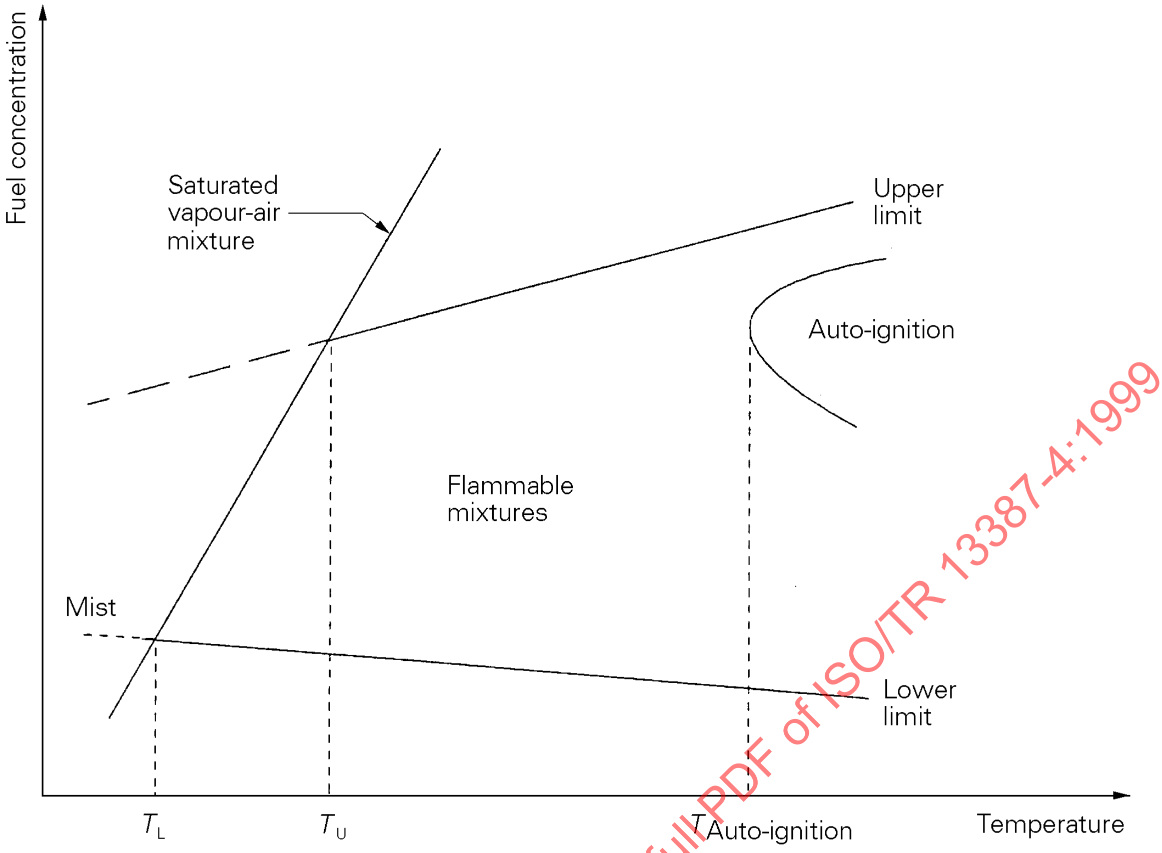


Figure 3 — Effect of temperature on the limits of flammability of a flammable vapour/air mixture at constant initial pressure[1]

Useful information on gas phase ignition can be found in references [1] and [2].

6.2.2.1 Input

The evaluation of gas phase ignition may require, as input, specific information on the following processes and product properties:

- fuel properties, e.g. latent heat of gasification, flash point, flammability limits, vaporisation or pyrolysis rate at defined temperatures and thermal-exposure histories;
- radiative, convective and conductive heat transfer to the surfaces to estimate the fuel flow rate and the thermal conditions in the space of interest;
- fuel/air mixing, e.g. the air flow in the space to estimate the dilution of the gaseous fuel;
- properties of potential ignition sources, e.g. temperature and spark energy.

Detailed discussions of the flammability of gas mixtures and ignition of liquid fuels, as well as tabulations of fuel properties, can be found in various publications, e.g. the SFPE Handbook[3].

6.2.2.2 Output

The output of the evaluation is the time to ignition or whether ignition will occur at all.

6.2.3 Ignition model for solids

Because most accidental fires in buildings are initiated on solid materials, this subclause is restricted to surveying the parameters that dominate the ignition of materials in the solid phase.

Heat transferred from a source to a target results in a rise in the temperature of the target. The conditions for ignition are produced when pyrolyzates from the target mix with air to produce ignitable mixtures at temperatures that could locally exceed spontaneous-ignition temperatures. The presence of any kind of pilot source will generally cause ignition as soon as the fuel/air ratio permits. Factors that control this process are the mode of ignition, the rate of heat transfer from the source, the target composition, the target location, the thermal and optical properties of the target and the availability of air. For common ignition sources (hot object, intense electric arc, smouldering material or flame), two types of ignition are possible: (1) glowing ignition (exothermic reaction at the surface of a material with air) and (2) flaming ignition (ignition that occurs in the gas phase mixture of pyrolyzates and air). Materials that ignite to glowing ignition may smoulder (combustion that occurs and propagates in the bulk material) for some period. If conditions are appropriate, smouldering may undergo a transition to flaming ignition and rapid fire spread. Materials that are ignited to flaming ignition may sustain the flaming mode and, if conditions are right, may spread to a larger size. Conversely, if the ignition experience is short, the flaming mode may be transient, and either convert to glowing or smouldering, or simply self-extinguish. As with the ignition process, the transient or sustained behaviour of the post-ignition condition is controlled by the composition and constitution of the material.

Regardless of ignition source, the response of a material to heating is dominated by the physical properties of the material. A detailed discussion of the ignition of solids can be found in reference [4]. Useful information can also be found in [5] and [6]. ISO/TC92/SC1 is working on a document describing the theoretical background of the ISO reaction-to-fire tests (ISO/TR 11696-1). The document includes a discussion of ignition under radiant heat exposure.

The thermal theory of ignition assumes that each material can be characterised by a critical ignition temperature T_{ig} [7]. By using simple heat-conduction theory, one can show that, for thermally thick material behaviour, the ignition delay is given by:

$$t_{\text{ig}} \propto k\rho c(T_{\text{ig}} - T_0)^2/(\dot{q}''_{\text{ext}} - \dot{q}''_{\text{loss}})^2 \tag{1}$$

For thermally thin material behaviour, i.e. if the temperature in the material is approximately uniform, the ignition delay is given by:

$$t_{\text{ig}} \propto \rho c L(T_{\text{ig}} - T_0)/(\dot{q}''_{\text{ext}} - \dot{q}''_{\text{loss}}) \tag{2}$$

The loss term $\dot{q}''_{\text{loss}}$ contains all the losses by re-radiation and convection.

The product property term $k\rho c(T_{\text{ig}} - T_0)^2$ or $\rho c L(T_{\text{ig}} - T_0)$ can be determined experimentally. This parameter has also been called a flux time product (FTP)[8],[9], and the square root of the parameter a thermal-response parameter (TRP)[10].

When deriving the equations above, all the properties have been taken as constants. In reality, the properties depend on temperature and other ambient conditions. For example, under slow heating the surface may pyrolyze sufficiently for the chemical properties to change, thus changing e.g. the ignition temperature. Usually, the experimental data available is from tests with a pilot ignition source. Without a pilot flame, the critical ignition temperature is considerably higher.

It may also be difficult to know whether the product is thermally thin or thick. The condition $L >> (\kappa t_{\text{ig}})^{1/2}$ is widely used for characterising products with thermally thick behaviour. Another practical rule of thumb is that a product is considered to show thermally thick behaviour if the physical thickness L is > 0,6$\rho\,\dot{q}''_{\text{ext}}$, where L is in mm, the density ρ in kg/m^3 and the heat flux $\dot{q}''_{\text{ext}}$ in kW/m^2 [8].

The loss term $\dot{q}''_{\text{loss}}$ depends on the ambient conditions, specimen size and orientation, etc. For example, different convective cooling of the surface may significantly influence the ignition delay time. One must therefore be very careful when applying the numerical data obtained even in standardised tests like the ISO ignitability test or the cone calorimeter. Proper corrections can be made if the conditions are sufficiently well defined.

At ignition, the loss term ($\dot{q}''_{\text{loss}}$) is equal to the critical heat flux for ignition. This is derived by extrapolation from a limited number of tests at different levels of radiant heat flux. However, the true minimum heat flux for ignition may be lower or higher because of the changes in the physical and chemical properties of the surface under extended exposure. The significance of this discrepancy depends to a great extent on the application of the data.

Special attention has to be given if the product under consideration melts. Some polymers that have low melting temperatures will melt away from moderate- to low-intensity ignition sources before the target attains its ignition temperature. It is therefore possible that product information based on some standard tests may not guarantee low flammability; under a higher exposure, the product may ignite easily.

The critical flux for ignition and the effective ignition temperature may be influenced by adding fire retardants to the solid. For some fire retardants, the effect may be to decrease the time to ignition under specific conditions. The benefit of the retardants is seen as a reduced burning rate.

In the above discussion, the intensity of the radiant source was assumed adequate to positively ignite a target. Normally, pure radiant sources would not cause the primary ignition in an accidental fire sequence. However, fire spread from an initially ignited item may occur by means of radiant heat transfer. Factors that define the radiant intensity of a source fire are flame area and thickness. The flame volume determines the flame emissivity, which is a number between 0 and 1. For hydrocarbon fuels, flames thicker than 1 m will generally have an emissivity approaching 1. This factor dictates the efficiency with which radiant energy is transferred between source and target. The flame size, along with the distance and angular intercepts between source and target, determines the view factor, which is also a number between 0 and 1.

View factors for various ideal shapes of hot objects can be found in reference [11]. Very often, flames from pool fires are treated as radiating cylinders the height of which depends on the burning rate or the heat release rate.

Flame size for most fuels is directly proportional to the mass burning rate or heat release rate. Correlation can then be created to enable the calculation of the minimum safe distance from a burning item[12].

6.2.3.1 Input

The evaluation of the ignitability of solids may require, as input, specific information on the following processes and product properties:

- fuel properties (thickness, surface emissivity, thermal conductivity, density, specific heat capacity, ignition temperature under various conditions, critical radiant flux for piloted ignition);
- radiative, convective and conductive heat transfer to the surfaces to estimate the fuel flow rate and the thermal conditions in the space of interest;
- properties of potential ignition sources, e.g. temperature and spark energy, size of flame.

6.2.3.2 Output

The output of the evaluation may be either the time to ignition or whether ignition is possible at all.

6.2.4 Ignition to smouldering

Materials which are prone to smouldering have particular chemical compositions, form char on decomposition and are generally low density (e.g. flexible polyurethane foams, cotton batting and pulverized-paper insulation). Contact with ignition sources such as cigarettes or hot surfaces can result in ignition which, if sustained, will propagate as smouldering combustion.

For cellulosic materials, the initiation of smouldering requires that the cellulose be converted to char, and this can occur after prolonged exposure to temperatures above 100 °C[13].

The same requirements have to be met for smouldering ignition of synthetic polymers to occur. In addition, these materials require a prolonged, low-intensity ignition source. Note that many of the conditions that promote smouldering combustion are similar to those necessary for self-ignition and spontaneous combustion, i.e. a material that is susceptible to oxidation, and an environment where the heat generated by oxidation is contained by a medium of low heat loss potential. Self-heating parameters are summarised succinctly in reference [14] and exhaustively in [15]. Many other sources of useful information on the assessment of self-ignition potential are available.

In the literature, the input data needed for evaluation of smouldering ignition is scarce. The self-ignition propensity is usually evaluated by a series of small-scale tests from which parameters are derived to enable evaluation of the critical storage temperature of a larger volume of the same product. The scaling laws are based on fundamental theory, and the extrapolation to larger scale has turned out to be remarkably reliable in a great number of applications.

6.3 Fire development

6.3.1 Evaluation of fire development

Evaluation of fire development is closely linked to the quantification of a design fire discussed in detail in ISO/TR 13387-2. There are basically two distinctly different methods of determining the design fire for a given scenario. One is based on knowledge of the amount, type and distribution of combustible materials in the compartment of fire origin. The other is based on knowledge of the type of occupancy, where very little is known about the details of the fire load.

The design fire and the fire development are usually quantified by the heat release rate (HRR) as a function of time. Once the heat release rate is known, the flame height and the gas temperatures in the room can be estimated using methods discussed later in this subclause. The external heating of a second object can then be calculated. The development of the fire can then be considered to be a sequence of non-simultaneous ignitions, which generally behave in the theoretical manner discussed in 7.1. A design fire can therefore be arrived at, using data from experiments to estimate the heat release rate and using methods outlined in 7.1 for calculating the time to ignition.

In some cases, more detailed methods can be used to simulate fire development. These may be needed especially when evaluating the relative fire safety of products in a specific application. Guidance on models of this kind will be given in the following subclauses describing the processes of fire development. It should, however, be noted that for design purposes the need for accurate data is not as high as for predicting the results of a single experiment. One may never cover all the possible fire situations and, therefore, characteristic data based on statistical data for a given occupancy must be applied.

Reference [16] provides a useful discussion about modelling fire growth from ignition to full involvement.

6.3.1.1 Input

The evaluation of the development of a fire (see Figure 1) requires as input information the following:

- building parameters (e.g. lining materials, thermal and chemical properties, location);
- fire loads (building contents, thermal and chemical properties of building contents, location);
- fire scenarios (e.g. experimentally determined characteristics of the first item ignited);
- thermal profile (radiative, conductive and convective heat fluxes, gas temperature, initial fuel temperature);
- building condition (conditions of the building products, e.g. due to pre-heating);
- contents condition (conditions of the building contents, e.g. due to pre-heating).

6.3.1.2 Output

The output data are:

- Size of fire/smoke (e.g. burning area, flame height, heat release rate, mass loss rate, smoke density in the room);
- thermal profile (temperature and heat flux distribution in the room of origin);

- pressure/velocity profile (e.g. pressure at smoke vents, flow through vents, velocity in the ceiling jet);
- building response;
- contents response.

6.3.2 Individual processes of fire development

In the following subclauses, we will discuss various components of fire development. The various processes are not always in the same form as in the bus illustration in Figure 1. For example, the different heat transfer mechanisms are listed in Figure 1 but not explicitly discussed here, because they are assumed to be general engineering knowledge.

In some engineering tools like the zone models, descriptions of different component processes are compiled into a single tool, making it possible to simulate the consequences of fire development. On many occasions, however, it is possible to consider the processes independently to draw the necessary conclusions concerning the required safety measures or the acceptability of a design.

6.3.2.1 Burning rate

The most important descriptor of a fire is the burning rate, which is quantitatively expressed as a heat release rate.

The burning rate may be calculated if the net heat flux to the surface and the latent heat of gasification are known. Unfortunately, neither of them are easily obtained for practical materials, because the properties of the fuels are time dependent and the net flux is affected by the flux from the flames of the burning item itself. The fuel vapours block (absorb) the radiation transmitted from the flame, and typically only a small fraction of the energy released by the flame can reach the surface. For horizontal pool fires, the net flux to the surface is only of the order of 1 % of the total heat release rate.

Often the only reliable way to estimate the burning rate is to use experimental data. Oxygen consumption calorimeters have been used to measure the burning rates of large-scale objects with rates of heat release of up to tens of megawatts[17]. Small-scale systems exist to measure the mass loss and heat release rates per unit area of specimens under well defined conditions. By applying modelling techniques of varying complexity, it is then possible to make reasonable estimates of the burning rates of larger objects, also under conditions differing from the conditions under which the input data was obtained. Useful sets of information on the burning rates of materials and products can be found in [10], [18] and [19].

Where it is not possible to characterize the combustible contents of the room of fire origin, fire growth is often assumed to increase with the square of time[20] using the relationship:

$$\dot{Q} = \dot{Q}_0 \, (t/t_g)^2 \tag{3}$$

where the so-called growth time t_g is the time to reach a heat release rate $\dot{Q}_0$. Often in the literature $\dot{Q}_0 \, t_g^{-2} = \alpha$. The value of α can be determined, in principle, based on statistical or experimental information on fire growth rates in different occupancies. So far, experimental and statistical data are scarce, and engineering judgement is therefore needed to determine the fire growth rate.

A parabolic fire is assumed to grow to a constant value when the fire becomes either fuel or ventilation limited. The burning rates at later phases of fire development are discussed in 6.3.3 and 6.3.4.

Sometimes the fire growth rate can be expressed as an exponentially growing fire. In fact, a fire spreading upward is more likely to grow exponentially than parabolically[21].

The idealised fire growth expressions have been criticised as being unrealistic[22]. However, for design purposes, when the exact type, location and geometry of the fire load is not known, no alternative approach has been proposed.

6.3.2.1.1 Input

Depending on the complexity of the model, the following input data are needed to estimate the burning rates of real objects:

- thermal conductivity, specific heat capacity and density of the product;
- heat of gasification;
- heat of combustion;
- radiative fraction of rate of heat release (typically 30 %);
- mass loss rate or rate of heat release per unit area (from small-scale tests under a known exposure);
- mass loss rate and/or heat release rate (from large-scale tests on real objects).

6.3.2.1.2 Output

The output data from the burning-rate evaluation are:

- mass loss rate;
- heat release rate;
- surface regression rate.

6.3.2.2 Smouldering

For cellulosic fuels, smouldering typically yields more smoke and unburned species per unit mass of fuel than flaming, but, because the fuel mass loss rate is low, the total-species generation rate is low. Smouldering may also provide a pathway to flaming at a later stage of the fire.

Smouldering usually occurs in low-density organic materials. Smouldering may be initiated by self-ignition or by a heat source embedded in the material or causing a heat flux at the appropriate level. A low heat flux may not be sufficient to ignite a smouldering fire and a high flux may immediately cause a flaming fire.

In fire safety engineering, consideration of smouldering is needed if the generation of visible smoke and toxic species is of interest at an early stage of the fire. Fire detection systems are often required to respond to a smouldering fire.

The models used to describe smouldering are often quite complex. Therefore, smouldering fires are often quantified based on experimental data. Like flaming fires, smouldering fires can also be described by the rate of heat release or mass loss rate as a function of time, although the burning rate is orders of magnitude lower. Experimental information is often in the form of the velocity of spread of the smouldering front. Combining the spread velocity with density data and estimates of the combustion process allows estimation of the mass loss rate or the rate of heat release of the fire.

Reference [23] is a useful source of information on the smouldering properties of various substances. Typical heat release rates of smouldering fires are given in [24].

Transition from smouldering to flaming combustion is undoubtedly a common process in fire growth scenarios. In many cases, smouldering can persist for hours before transition, and this fact can be crucial in situations where the initiation site is hidden, or separated from areas of activity. Increased air flow in the direction of smoulder propagation is critical for transition to flaming. This effect is influenced by pre-heating of virgin fuel by the air that passes over the active smouldering region. A practical example of this phenomenon occurs when a smouldering front breaks out of the side of an upholstered chair, and immediately encounters excess air for the combustion zone and a heated convection plume on the vertical exterior surfaces of the chair. Another transition mechanism is analogous to the conditions of self-heating. Because smouldering is an oxygen-deficient process, the temperature of the smouldering front is relatively low. However, surface layers insulate the internal reaction zone so that internal temperatures become quite high and the reaction region porous. This porosity enhances air transfer to the interior, thus intensifying the reaction to produce persistent local flaming.

The transition to flaming is so sensitive to ambient conditions, variations in the porosity, etc., that it is practically impossible to predict the time it takes for smouldering to turn into flaming combustion. For building design, this kind of consideration is seldom needed, although for life safety assessment in the room of origin one may need to assume an extended period of smouldering.

6.3.2.2.1 Input

The input data used to describe a smouldering fire may include:

- the velocity of spread of the smouldering front;
- the density and chemical composition of the fuel;
- the combustion efficiency and the heat of combustion of the fuel.

6.3.2.2.2 Output

The output information describing a smouldering fire may be:

- the mass loss rate or the heat release rate of the fire.

6.3.2.3 Flame size

The size of the visible flame can be used to further calculate the radiative heat flux from the fire to a remote object. It is also needed to determine the appropriate expressions for the temperature and velocity distributions in or near the fire plume, i.e. different expressions are needed if the point of interest is inside the visible flame, inside the convective plume above the fire or completely outside of the fire plume.

The flame size is directly proportional to the rate of heat release in the fire. Typically, the rate of heat release per unit volume of flame is in the range 0,5 MW/m^3 to 2 MW/m^3 of visible flame. Various expressions are available for the flame height as a function of the rate of heat release, as discussed in [25]. Reference [26] includes information on flame sizes and the subsequent view factors of large open hydrocarbon pool fires.

6.3.2.3.1 Input

The input information needed to calculate the flame size is:

- heat release rate and diameter of the fire;
- heat release rate per unit width of a wall fire.

6.3.2.3.2 Output

The output from the evaluation of the flame size is:

- size of the flame, especially the flame height.

6.3.2.4 Flame heat fluxes

The impact of fire on the building fabric or building contents depends to great extent on the heat flux received by the object. The heat flux received depends on the view factor (the geometric characteristics of radiation exchange) and the flame properties, such as the temperature profile and optical properties (emissivity), depending on the nature of the fuel, the fuel/air ratio and the shape and dimensions of the flame.

There are no easy-to-use hand-calculation methods for accurately estimating the heat flux from a flame of arbitrary size and shape. In the case of small flames, both the convective and radiative components may vary considerably, depending on the size and shape of the flame and the way it makes contact with the object. For example, the flux from a 100 kW flame against a wall is of the order of 25 kW/m^2, but a 10 kW flame impinging on a ceiling may cause a heat flux of the order of 60 kW/m^2 to the stagnation point. The thicker the flame becomes, the higher the flux. For example, a 0,5 m × 0,5 m gas burner in a corner with a heat release rate of 300 kW may cause a flux of 100 kW/m^2. In a fully developed room fire, considerably higher heat flux levels can be found. A recent review includes experimental data on heat fluxes in different experimental conditions[27].

6.3.2.4.1 Input

The input information needed to evaluate the flame heat flux may include:

- heat release rate and type of fuel;
- size of the fire source and position with respect to the object;
- thermal properties of the object.

6.3.2.4.2 Output

The output of the heat flux evaluation is:

- total heat flux and/or its components;
- heat transfer coefficients between the flame and the surface.

6.3.2.5 Flame spread on solids

Flame spread on walls, ceilings and floors in rooms is a complicated process, depending both on the properties of the surface products and the ambient conditions in the room. The problem is usually divided into two different cases according to the different relative directions of air flow and flame propagation[28],[29]. In the wind-aided (concurrent, upward) flame spread case, air flow is in the same direction as flame spread. In the opposed-flow (countercurrent, downward or lateral) flame spread case, air flow is in the opposite direction to flame spread. The former case is usually orders of magnitude faster than the latter.

The heat flux from the flame to the surface in front of the proceeding flame front in opposed-flow flame spread depends to some extent on the gas phase thermal properties of the pyrolyzed fuel. These properties are difficult to measure independently, and therefore experimental data from lateral flame spread tests are needed in the engineering models describing opposed-flow spread on walls. A detailed discussion of the lateral flame spread models using standard test data can be found e.g. in ISO/TR 11696-1.

When flames are spreading on a horizontal surface like a mattress, the source flame may become so high and thick that the radiative flux from the flame becomes high enough to dominate the spread process compared to gas phase conduction. In such cases, the lateral spread can be described by using data available from the cone calorimeter (ISO 5660), i.e. the time to ignition characterising the thermal response, the ignition temperature of the fuel surface and the rate of heat release determining the size of the flames. There is still only a limited number of examples of the success of these kinds of models. Therefore, calibration of the models against experimental data is extremely important before extending the use of the models outside the product category.

During recent years, considerable advances have been made in the development of thermal models for upward flame spread. The basic equation used is:

$$\frac{\mathrm{d}x_\mathrm{p}}{\mathrm{d}t} = \frac{x_\mathrm{f} - x_\mathrm{p}}{\tau} \tag{4}$$

where

x_p is the position of the pyrolysis front;

x_f is the flame height;

τ is a time constant which is usually taken as the time to ignition at an appropriate heat flux level[16].

The flame height is proportional to the total heat release rate per unit width of wall. A number of analytical and numerical schemes exist to solve equation (4) and to obtain the associated heat release rate. The model and its applications are discussed in more detail in ISO/TR 11696-1. The majority of the models based on equation (4) use the results of the cone calorimeter test as input data. Typically, data taken at irradiance levels between 25 kW/m^2 and 35 kW/m^2 have proven applicable.

The models based on equation (4) can be used e.g. to consider whether the fire will spread or not. When the heat release rate is calculated as a function of time, one may also estimate whether flashover will occur and, if it occurs, the time to flashover.

Recently, work has also been done to implement flame spread in computational fluid-dynamics models. Although in principle one could use more fundamental input data, the most promising practical applications are those in which the lining response and pyrolysis under thermal exposure are taken from the same standard tests as those in the model discussed above.

One should note that the flame spread models do not account for flaming droplets which may accompany flame spread over thermoplastics, nor falling pieces that may accompany flame spread on charring materials at a later stage of the fire.

6.3.2.5.1 Input

The input data needed for evaluating flame spread are e.g.:

- time to ignition and rate of heat release per unit area as a function of time at an appropriate irradiance level;
- the flame spread parameter derived from a standard lateral flame spread test.

6.3.2.5.2 Output

The output of a flame spread evaluation is e.g.:

- burning area as a function of time;
- heat release rate of a spreading fire;
- size of the spreading flames (flame height).

6.3.3 Room effects on fire growth

If the fire is initially sufficiently small and sufficiently far from the walls, it can be treated as if it were in the open. If the fire is close to a wall, the entrainment from the side of the wall is limited, causing the flames to become longer and the temperatures in the plume to become higher. This may be of importance, e.g. if the ceiling is made of ignitable or burning-dripping material.

The second effect of the room is the accumulation of a hot gas layer in the upper part of the room. The hot gas entrained from the upper layer into the plume is warmer than air, and hence the temperature in the plume decreases more slowly as a function of height. If the flame is so high that combustion takes place in the vitiated air of the smoke layer, combustion efficiency may be reduced and a larger fraction of the combustible vapour (pyrolyzate) may survive. When the temperature of the upper layer increases, the hot layer begins to radiate on all the surfaces in the room. As the temperature of the upper layer approaches 500 °C, the heat flux becomes so high that all the combustible surfaces in the room may ignite in a few seconds, i.e. flashover may occur[5].

Hot walls, heated by a flame close to the wall or by the upper layer, may also radiate back to the fuel surface, causing the fuel flux to increase and the fire to grow faster than without the presence of the wall.

6.3.4 Ventilation-controlled fires

After flashover, the mass loss rate can become so high that there is not enough oxygen available to burn all the fuel. The mass loss rate in the room remains approximately constant and the openings usually restrict the inflow of air to keep the heat release rate inside the room constant as well. The design fire at this point can be characterised by a constant rate of heat release, and the gas temperatures inside the room then depend on the heat balance between the generation of heat (combustion) and the loss of heat through the openings and to the boundaries. The temperature may often be assumed homogeneous inside the room.

Several methods have been developed to describe the temperatures in a ventilation-controlled fully developed fire. Typically, the burning rate in an enclosure has been found to depend on the ventilation factor:

$$F_\mathrm{v} = A_\mathrm{v} \times (h_\mathrm{v})^{1/2} \tag{5}$$

The gas temperature in the enclosure depends on the thermal properties of the boundaries and an opening factor:

$$F_0 = A_\mathrm{v} \times (h_\mathrm{v})^{1/2}/A_\mathrm{T} \tag{6}$$

where A_T is the total area of the compartment-enclosing surfaces.

A discussion of the maximum temperatures to be found in fully developed fires can be found in reference [30]. The reference also contains a brief discussion of the parametric time-temperature curves of ventilation-controlled fires. The parametric time-temperature curves express the temperature of a fully developed fire as a function of time, the thermal properties of the room boundaries, and the opening factor. These curves are already being applied, e.g. in the structural Eurocodes for designing fire-resistive structures.

According to reference [5], the highest temperature for wood crib fires in small enclosures can be found if $A_\mathrm{v}(h_\mathrm{v})^{1/2}/A_\mathrm{T} = 0{,}08\ \mathrm{m}^{1/2}$. For smaller values, there is excess fuel and for higher values excess air. For values more than about 0,11 $\mathrm{m}^{1/2}$, the fire is fuel controlled. It has also been suggested that wood crib fires become fuel controlled when $A_\mathrm{v}(h_\mathrm{v})^{1/2}/A_\mathrm{fuel} > 0{,}08\ \mathrm{m}^{1/2}$ [31]. Reference [32] presents a more detailed model for assessing the burning rates of wood cribs. It is shown that the fire is fuel controlled if the burning rate of the crib is less than $0{,}12A_\mathrm{v}(h_\mathrm{v})^{1/2}$. For a room of normal height with a normal-size door, this limiting value is well above the burning rate required to cause flashover, indicating that flashover may occur before the fire is fully developed.

6.3.4.1 Input

When assessing the burning rates and temperatures of ventilation-controlled fully developed fires, the following information is needed:

- fire load density in the room;
- dimensions of the room and the openings therein;
- thermal properties of the bounding walls, floor and ceiling.

6.3.4.2 Output

The output of the evaluation of a fully developed ventilation-controlled fire include:

- maximum burning rate;
- maximum heat release rate inside the room;
- temperature as a function of time inside the room.

6.3.5 Decay of a fire

As the fire load begins to be exhausted, the burning rate starts to decrease. The decay period typically begins after 80 % of the fuel has burned. However, if the fire load is to a significant extent as wall and ceiling linings, the decay period may begin later and consequently be much shorter. The decay period is usually considered together with and as a direct continuation of the ventilation-controlled fully developed fire and, therefore, the same calculation methods apply as described in the previous subclause.

6.4 Smoke production

6.4.1 Evaluation of smoke production

Smoke is produced in all fires. It evolves from all kinds of combustible building materials used in load-bearing constructions, insulation, surface linings, installations or building contents like furniture or stored goods. The rate of smoke production is dependent on many factors. Smoke poses a threat to occupants and to fire brigade personnel, causing reduced visibility and endangering evacuation and rescue. The smoke particulate may cause irritation and subsequent incapacitation and, at worst, death.

According to the definition in ISO 13943, smoke is a visible suspension of solid and/or liquid particles in gases resulting from combustion or pyrolysis. Reference [33] defines smoke as the smoke aerosol or condensed-phase component of the products of combustion. Sometimes, however, the evolved gases have been included in the definition as well[34].

Here, only the particulates are discussed. These particles are not at all homogeneous, neither in size nor in composition. As described later, the rate of smoke production, and thereby the smoke particulate, vary with the material of origin, exposure and combustion conditions, and with time.

Smoke particles reduce visibility due to light absorption and scattering. Consequently, people may have difficulty in finding escape routes. A practical way to quantify visibility is the distance at which an object is no longer visible. Depending on smoke movement, the hazardous area can be large and the smoky environment can expand very fast.

Corrosive effects on building structures and contents have become an area of great concern and have prompted a number of regulating bodies to restrict or prohibit the use of materials identified as generating corrosive smoke, i.e. halogenated cable and wire insulations.

Most of the technical literature on smoke production from building materials presents experimental results in small-scale tests. There is not much information available in the scientific literature concerning modelling or predictive correlations between small-scale smoke data and real fires or large-scale test results[35],[36]. The scale dependence of the rate of smoke production is generally not very well known.

Different systems of units are used to describe the smoke density, causing a potential for misinterpretation of experimental data. The different systems of units are described in annex A. It is recommended here to use the natural-logarithm-based system of units, i.e. to characterise the optical smoke density by its extinction coefficient:

$$K = \frac{1}{l} \ln \frac{I_0}{I} \qquad (7)$$

where

I_0 is the intensity of light in clean air;

I the intensity of light after passing a distance l (optical path length) through the smoke.

The reason for selecting this system of units is that the majority of data quantitatively characterising the smoke production propensity of products is now generated in these units. The smoke production propensity of a material is now described in units of m^2/s. If the burning rate is measured, the smoke production propensity can be scaled to m^2/kg of material burned, or m^2/J if only the rate of heat release is measured.

One should also note that the extinction coefficient depends on the wavelength of light. According to [37], the extinction coefficient is inversely proportional to the wavelength. If the data is measured with a system operating in the near-infrared, the true extinction coefficient at the wavelength of visible light is somewhat higher.

The unit of area is appropriate since it describes the effective cross-sectional area of the smoke particles. By combining the quantitative information on the amount of smoke produced with the burning-rate information, one is able to estimate the smoke density in locations away from the fire source as is described in ISO/TR 13387-5.

Another method of describing the amount of smoke produced is by the smoke yield, i.e. by the mass of smoke generated per mass of fuel burned. If the fuel mass loss rate is known, one is then able to estimate the mass of smoke generated. The data on smoke yield has the advantage, compared to the above-mentioned smoke generation rates, that no confusion in the units is possible.

6.4.1.1 Input

The evaluation of smoke generation requires as input information the following:

- building parameters (e.g. lining materials, chemical properties, location);
- fire loads (building contents, chemical properties, location);
- fire scenarios (e.g. experimentally determined characteristics of the first item ignited, including rate of smoke production);
- environmental parameters (e.g. humidity).

6.4.1.2 Output

The following output information is produced:

- Size of fire/smoke (rate of smoke production either as specific are per unit time or mass per unit time).

6.4.2 Factors influencing smoke production

6.4.2.1 Composition of product

The chemical nature of the burning material has a systematic effect on the smoke production. Some pure fuels (e.g. carbon monoxide, formaldehyde and methyl alcohol) do not produce smoke if burned with sufficient ventilation. Other organic materials burning under identical conditions may give substantial amounts of smoke, depending on their chemical nature. Organic liquids which are oxygenated (such as ethyl alcohol) give less smoke than corresponding hydrocarbons. If the hydrocarbons are unsaturated, the smoke production is higher than with corresponding saturated hydrocarbons. Similar observations are true for solids. Oxygenated fuels, such as wood, give less smoke than do hydrocarbon polymers such as polyethylene. Aromatic compounds, such as polystyrene, produce by far the greatest amounts of smoke[35].

6.4.2.2 Environment

The smoke production may also depend on the burning environment. Experimental studies have shown smoke yield to be dependent on variables such as radiant heat flux, oxygen concentration, ventilation, sample orientation and geometry, and the moisture content of the sample[35]. Most of these conditions can also vary between different phases of a fire. However, two distinct phases of smoke production should be considered, one related to the early stages of fire (pre-flashover, perhaps only a single item involved), and another related to the post-flashover fire (all items of a compartment are burning under ventilation-controlled conditions).

The rate of burning and the area involved in burning must always be considered when determining the smoke production. A material or product producing rather small amounts of smoke per fuel area may have a substantial smoke production due to a rapid surface spread of flames. This is of special importance when comparing fires (or tests) of different sizes. At low O_2 concentrations, the smoke yield may increase significantly. In a compartment fire, the smoke generation rate has been found to increase when the fuel-to-air equivalence ratio is close to or higher than one (see 6.5.2).

6.4.2.3 Combustion

Smoke is basically a product of incomplete combustion. In smouldering combustion, volatiles are evolved at elevated temperatures. Upon mixing with cool air, they condense to spherical droplets, which appear as a light-coloured smoke aerosol. The size of the spherical droplets from smouldering combustion is generally of the order of roughly 1 mm, i.e. larger than from flaming combustion.

Flaming combustion produces a black carbon-rich smoke, in which the particles have a very irregular shape. The smoke particles from flaming combustion are formed in the gas phase and in regions where the oxygen concentrations are low enough to cause incomplete combustion. For cellulosic materials, the amount of smoke per unit mass is less with flaming combustion than with smouldering combustion. With plastics, however, no such generalisation can be made. For wood and similar cellulosic materials, the production of smoke is increased dramatically with restricted ventilation; for other types of fuel, little is known.

6.4.2.4 Fire and flame retardants

Quantitative smoke data regarding fire retardant (FR) treated materials or products is scarce[38]. One also has to be very careful with the use of data from products with generic names, because the differences in actual treatments may cause significant differences in smoke production properties. The yields of smoke for FR products may be higher than for corresponding untreated products. However, in real-scale tests it has been demonstrated that, if sufficiently effective FR agents are used, any effects of increased yields of smoke are more than compensated for by decreased burning rates of polymeric materials.

6.4.2.5 Smoke maturation

It is generally known that the particle size increases as a function of time due to agglomeration after collision of particles with each other. The literature considering this effect is scarce and still on a relatively theoretical level. A model to take into account the smoke maturation has been developed[39], but it has probably never been applied in practical fire safety engineering.

6.4.3 Available smoke data

Despite the large number of laboratories using different fire-testing methods, published smoke data are scarce. Smoke yield data for a large number of materials can be found in [10]. A large number of smoke obscuration values have been tabulated in [40]. Compilations from cone calorimeter measurements have been published for a few materials in [41], for upholstered furniture materials in [19], [41] and [42], for fire-retarded materials in [21], and for some building products in [35] and [43]. References to the older literature on smoke evolution can be found in [44].

Data on the smoke production of different materials are available mainly from small-scale testing (specific optical density, mass optical density). However, when using such data, it should be noted that there are substantial differences for the same or similar materials under almost similar burning and testing conditions[35]. It should be emphasised that these smoke data represent a general level rather than "absolute" properties for different materials and products. Measurement of smoke is essentially dependent on the equipment used, and interpretation of time-dependent curves is not very simple.

In laboratory experiments, the production of smoke and its optical properties are often measured simultaneously with other fire properties as heat release rate and flame spread. The measurements are usually dynamic in full-scale testing, i.e. they are performed in a flow-through system. In small-scale testing, they may be either dynamic, as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. Small-scale tests are necessary as practical tools. Full-scale tests are generally considered to be more reliable and are needed to establish the utility of the small-scale tests.

The use of smoke point data to characterise the smoke production propensity of products has also been considered[10]. A recent paper[45] describes the methodology, but it is not yet at a level applicable for fire safety engineering at large. Standard methods are available for measuring the smoke points of gaseous and liquid fuels[46], but not solid fuels.

6.4.4 Prediction of smoke production in large-scale fires

Quantitative prediction of the rate of smoke production using basic principles for commercially available construction products is not possible at the moment. Therefore, test-based correlation models are needed to be able to use small-scale test data in determining the fire hazard of products.

The prediction of smoke production has been studied much less than the prediction of heat release, and with limited success so far[35],[36]. However, there seems to be some evidence that the early stages of certain full-scale scenarios can be predicted, although the post-flashover smoke production cannot be resolved yet. As one main recommendation to obtain correlations between small-scale and large-scale data, flow-through systems have been suggested[35].

Smoke data in units where the specimen mass is normalised are preferred for correlations with full scale, but are often hard to determine in full-scale fires. In cases where mass-normalised data have not been obtained for the full scale, parameters describing the burning rate should be included in correlations between small-scale and full-scale smoke production. An alternative is to normalise the smoke production in small scale and full scale to the heat release rate.

One possible way to develop useful correlations is to use smoke mass yields. The mass concentration information could then be translated into optical densities. According to [47], the total cross-sectional area of smoke (see annex A for definitions) particulate per mass of smoke is about 7 600 m^2/kg of smoke for flaming fires and 4 400 m^2/kg of smoke for smouldering fires. More recent data suggest that a typical value for flaming fires would be close to 10 000 m^2/kg.

The correlation between small-scale and large-scale tests breaks down as the fire becomes complex. For design procedures based on humans evacuating through a smoke-filled section of a building, it is necessary to make sensitivity calculations, incorporating smoke production data from underventilated fires if such a scenario can be envisaged.

6.5 Species generation

6.5.1 Evaluation of species generation

In ISO terminology, a fire effluent is the total gaseous, particulate or aerosol effluent from combustion or pyrolysis. It is important in the understanding of species generation to note that some toxic species are material-dependent, while others are dependent on the conditions of the fire itself. Since combustion is an oxidation process, it results in organic species being transformed to some oxidised state, the extent depending upon the ventilation conditions or oxygen supply. Organic species are oxidised to aldehydes, organic acids, carbon monoxide (CO) and carbon dioxide (CO_2). The CO/CO_2 ratio, often used as a descriptive characteristic of a fire, depends more upon the ventilation conditions of the fire than on the nature of the materials being burned.

The formation of HCN during thermal decomposition is material-dependent, with only nitrogen-containing products yielding HCN. In addition to being material-dependent, HCN production is also temperature-dependent, with high temperatures favouring HCN formation. If sufficient oxygen is present, low concentrations of oxides of nitrogen (NO_x) and some nitrogen may also be formed.

Polymer systems containing halogen (fluorine, chlorine or bromine) result in the formation of the halogen acids (HF, HCl and HBr), the production of which is material-dependent. The halogen acids are formed in the pyrolysis component of the combustion process and are not oxidised further. Thus the halogen acids are produced even if flaming combustion does not occur.

Reference [10] contains a detailed discussion of species generation and also provides quantitative data on the yields of various species. Further guidance can be found in ISO 13571.

6.5.1.1 Input

The evaluation of smoke generation requires as input information the following:

- building parameters (e.g. lining materials, chemical properties, location);
- fire loads (building contents, chemical properties, location);
- fire scenarios (e.g. experimentally determined characteristics of the first item ignited, including rate of smoke production);
- environmental parameters (e.g. humidity).

6.5.1.2 Output

The following output information is produced:

- Effluent/species (rate of species production).

6.5.2 Carbon monoxide

Carbon monoxide is produced both from smouldering and from flaming combustion. The production of CO from smouldering fires is a very complex combustion process. Although it has been the object of numerous studies, the state of knowledge is still insufficient to enable the calculation of CO production with the confidence needed for the assessment of the threat to life in a design fire. This part of ISO/TR 13387 will, therefore, focus on CO production only from flaming combustion.

The production of CO from the flaming combustion of materials is largely dependent upon the supply of oxygen. Oxygen available to a fire can be limited either by lowering the oxygen concentration in the incoming air supply or by a reduction in the volume flow of air to a fire.

The formation of CO is related to the fuel-to-air equivalence ratio, which is defined as:

$$\phi = \frac{\mathrm{kg_{fuel}} / \mathrm{kg_{air}}}{(\mathrm{kg_{fuel}} / \mathrm{kg_{air}})_{\mathrm{stoich}}} \qquad (8)$$

where "stoich" denotes conditions at which the ratio between fuel and oxygen is that required for complete combustion with no excess oxygen. Thus, when $\phi = 1$, exactly stoichiometric conditions exist between fuel and air. For values of $\phi < 1$, the fire is well ventilated; for values of $\phi > 1$, the fire is fuel-rich and ventilation-controlled. These latter conditions are ones that favour the formation of CO[10],[48],[49].

NOTE Some investigators use an air-to-fuel equivalence ratio, rather than one of fuel-to-air[5]. In that event, the air-to-fuel equivalence ratio would be equal to $1/\phi$ as used here.

Production of CO is generally expressed in terms of its yield, i.e. the mass of CO produced per unit mass of fuel, $\mathrm{kg_{CO}/kg_{fuel}}$. The rate of CO production can be calculated from the yield and the fuel mass burning rate. For use in the modelling of the toxicological effects of CO, the rate of formation of CO in mass produced per unit time must be converted to concentration by volume over time.

Studies[10],[48] have shown that under well ventilated conditions ($\phi << 1$), yields of CO are very low. These yields remain negligible until ϕ reaches about 0,5. Thereafter, the yields of CO increase rapidly as values of ϕ increase, reaching a plateau for most materials in the range from 0,1 to 0,2 at an equivalence ratio of somewhat greater than 1,0.

For rooms approximately the size of that in the ISO 9705 room fire test, flashover occurs at about the time when ϕ reaches 0,5[10]. This is also the point at which CO yields begin to rise dramatically. Thus, a rapid increase in CO yield occurs almost simultaneously with flashover. At flashover, the rate of CO production also increases dramatically since it is dependent on the mass burning rate, which increases rapidly at flashover. Thus, the rapid rise in CO production at flashover is due both to the fire becoming ventilation controlled and to the very rapid rise in the mass burning rate. These phenomena have been observed with large-scale fire tests involving fully furnished rooms[49],[50].

From the aspect of the toxic hazard due to CO, there is little concern with well ventilated fires since both yields and rates of CO production are quite low. Although a model has been proposed to calculate CO yields as a function of equivalence ratio, only modest agreement with experimental data has been shown[51]. Moreover, most fires pass through the range $\phi = 0,5$ to $\phi = 1,0$ quite rapidly. Once ϕ reaches a value greater than 1,0, the CO yield becomes fairly constant. The production rate is then dependent only on the mass burning rate. For a sufficiently large fire whose flame radiative heat flux and material-vapour mass generation rate have approached their asymptotic values, the mass burning rate remains fairly constant and, thus, the CO production rate is also constant[49].

6.5.2.1 Processes

The CO production rate $\dot{m}_{\mathrm{CO}}$ can be estimated from equation (9):

$$\dot{m}_{\mathrm{CO}} = f_{\mathrm{CO}}\ \dot{m}_{\mathrm{fuel}} \qquad (9)$$

where

f_{CO} is the yield of CO;

$\dot{m}_{fuel}$ is the fuel mass burning rate, usually in kg/s.

Under post-flashover conditions in the absence of definitive values, f_{CO} may be assigned a value of 0,2.

Equation (9) gives the rate of CO production in units of mass per unit time. To be useful in the modelling of toxic hazard, these units must be converted to ppm (parts per million) by volume in the enclosure. With ρ_{CO} equal to the density of CO (1,25 kg/m^3 at standard temperature and pressure) the volumetric production rate can be expressed as $\dot{V}_{CO} = \dot{m}_{CO} / \rho_{CO}$.

6.5.2.1.1 Input

Required are:

- mass burning rate $\dot{m}_{fuel}$;
- carbon monoxide yield f_{CO}.

6.5.2.1.2 Output

Produced is:

- carbon monoxide generation rate $\dot{m}_{CO}$ or $\dot{V}_{CO}$.

6.5.3 Carbon dioxide

For well ventilated fires, i.e. $\phi << 1$, essentially all the fuel carbon is oxidised to CO_2. Thus, the yield of CO_2 is essentially quantified. With ventilation-controlled fires, the production efficiency is still high (90 % to 95 %); however, more carbon appears as CO, soot and unburned organic species. It is important to note that the mass of carbon is conserved under all combustion conditions.

6.5.3.1 Processes

The yield of CO_2 from the burning of a fuel is most readily calculated by multiplying the maximum possible yield, obtained from its chemical composition, by its production efficiency which in the case of CO_2 is very high, i.e. about 90 % to 95 %[10]. If the chemical composition of the fuel is known, the maximum yield f_{CO_2} is given by:

$$f_{CO_2} = \frac{44}{\text{Molecular mass of simple empirical chemical formula of fuel (i.e. } CH_xO_yN_z\text{...)}}$$

As with CO, the yield of CO_2 must be converted to its generation rate by multiplying by the fuel mass burning rate. The resulting mass production rate must then be converted to units of ppm (or preferably percent) of CO_2 accumulated per unit time, analogous to those operations performed for CO.

6.5.3.1.1 Input

Required are:

- empirical chemical formula of fuel (use CH_2 for natural fuel if exact formula is unknown);
- mass burning rate $\dot{m}_{fuel}$.

6.5.3.1.2 Output

Produced is:

— carbon dioxide generation rate $\dot{m}_{\mathrm{CO_2}}$ or $\dot{V}_{\mathrm{CO_2}}$.

6.5.4 Hydrogen cyanide

In contrast to the extensive work with carbon monoxide, there have been insufficient studies of HCN formation to enable its generation in fires to be quantified mathematically. The maximum possible yields of HCN can be estimated; however, these are not likely to be suitable for use in calculations of the threat to life of fires.

6.5.4.1 Processes

The maximum possible yield of HCN (i.e. assuming all nitrogen is converted to HCN) may be calculated as:

$$f_{\mathrm{HCN}}(\mathrm{max.}) = \frac{27}{\text{Molecular mass of simple empirical chemical formula of fuel } (\mathrm{C}_{1/z}\mathrm{H}_{x/z}\mathrm{O}_{y/z}\mathrm{N})}$$

The production efficiency of HCN and its dependence on the various fire parameters are not known. Thus, only maximum yields and rates of production based on mass burning rates can be calculated using methods analogous to those for CO_2.

6.5.4.1.1 Input

Required are:

— empirical chemical formula of fuel;

— mass burning rate $\dot{m}_{\mathrm{fuel}}$.

6.5.4.1.2 Output

Produced is:

— maximum possible HCN production rate $\dot{m}_{\mathrm{HCN}}$ or $\dot{V}_{\mathrm{HCN}}$.

6.5.5 Hydrogen halides

The maximum possible yields of the hydrogen halides can be calculated as with other species. Since the production efficiencies for the formation of HF, HCl and HBr are likely to be close to 1, maximum production yields would be expected in fires. It should be noted that hydrogen halide concentrations also decay rather quickly in the presence of sorptive surfaces and water droplets present in most fire effluents at temperatures below 100 °C. Thus maximum possible concentrations are rarely actually measured[52].

6.5.5.1 Processes

The maximum possible yields of hydrogen halides may be calculated, as with CO_2, from:

$$f_{\mathrm{HX}} = \frac{\text{Molecular mass of halide}}{\text{Molecular mass of simple empirical chemical formula of fuel } (\mathrm{C}_{1/w}\mathrm{H}_{x/w}\mathrm{O}_{y/w}\mathrm{N}_{z/w}\mathrm{X})}$$

As with CO, the yield of HX must be converted to production rate by multiplying by the fuel mass burning rate. The resulting mass production rate must then be converted to units of ppm produced per unit time, again analogous to those operations for CO.

One should, however, note that hydrogen halides may be generated by thermal degradation even before ignition and, consequently, this simple approach may lead to errors. When halides are contained in the fuel, it is necessary to make assumptions concerning hydrogen consumption to be able to write the stoichiometric reaction. For instance, fluorine F_2, due to its strong electronegativity, combines in priority with hydrogen to form HF. Chlorine Cl_2 then combines with hydrogen to form HCl and, finally, hydrogen is oxidised to form water vapour H_2O.

6.5.5.1.1 Input

Required are:

- empirical chemical formula of fuel;
- mass burning rate $\dot{m}_{\mathrm{fuel}}$;
- information on the chemical processes involved.

6.5.5.1.2 Output

Produced are:

- maximum possible HF, HCl or HBr production rate $\dot{m}_{\mathrm{HX}}$ or $\dot{V}_{\mathrm{HX}}$;
- maximum possible HF, HCl or HBr accumulation rate.

7 Engineering methods

7.1 General

During the last decade, real progress has been made in the understanding of fire processes and their interaction with humans and buildings. Advance has been particularly rapid where analytical fire modelling is concerned. A number of models, with varying degrees of complexity, have been developed in recent years. The models can be classified as being either deterministic or probabilistic.

Field models or CFD (computational fluid dynamics) models are deterministic models in which the enclosure volume is divided into a very large number of sub-volumes and the basic laws of mass, momentum and energy conservation are applied to each of these. A second type of deterministic fire model is one on which the room is divided into a limited number of control volumes or zones. The most common type is termed a "two-zone model" where the room is divided into an upper hot zone and a lower cold zone. The equations for mass and energy conservation are solved numerically for both zones at every time step. Both zone models and field models are discussed in more detail in ISO/TR 13387-5. Conceptually close to the zone models are deterministic models which describe fire growth in a specific scenario like the models for fire growth in the room/corner test.

A third way of analytically describing some basic fire processes is to use simple hand calculation methods which, by broad definition, include procedures implemented as spread sheet programmes or similar small computer codes to give results for analytical equations. These are basically a collection of simplified solutions and empirical methods to calculate flame heights, mass flow rates, temperatures and velocities in fire plumes. The so-called meta-models obtained by fitting an analytical function to results of a series of numerical calculations also belong to this category. Hand calculations are not only for solving fire-related problems as such, but another important area of use is to check the relevance of the results of evaluations made using large-scale experiments or numerical computer codes.

A fourth type of fire development model is the probabilistic model, which does not make direct use of the physical and chemical principles involved in fires, but makes statistical predictions about the transition from one stage to another. The course of a fire is described as a series of discrete stages that summarise the nature of the fire. Time-dependent probabilities are ascribed to the possibility of the fire changing from one stage to another. These are determined from a knowledge of extensive experimental data and fire incident statistics.

It should be noted that all these models can be combined in various ways (deterministic with probabilistic, two-zone with field models, etc.) to form hybrid models. Whatever the calculation method is, the principles of ISO/TR 13387-3 should be followed to assess the applicability of the method.

In spite of the development of calculation models, experiments still have a significant role in fire safety engineering. They are needed to produce input data for calculation models, to produce reference data to add confidence to the results of calculations and often also as a direct means of getting answers to design problems.

7.2 Estimation formulae

The hand calculation methods can be divided into three categories: those that deal with heat transfer, those that deal with combustion and those that estimate the resulting conditions. These methods have variable limits of application which should be checked by the user.

7.2.1 Heat transfer

There are three mechanisms by which heat is transferred from one object to another: radiation, convection and conduction. Classical textbooks on heat transfer provide innumerable hand calculation expressions for calculating heat fluxes to and from solids, liquids and gases as well as expressions for estimating the resulting temperature profiles in a target. These analytical expressions are usually arrived at by setting up the energy balance, by assuming constant properties and homogeneity in the media involved and by ignoring the heat transfer mechanisms which seem to be of least importance in each case.

The radiative heat flux from flames, hot gases and heated surfaces impinging on a solid surface can be estimated using classical heat transfer theory and view factors. The same applies for convective heat transfer to solids and conductive heat transfer through solids. The surface temperature of a solid subjected to a radiative, convective or conductive heat flux can be calculated by hand, assuming the solid to be either semi-infinite or consisting of a lumped thermal capacity.

7.2.2 Fire development and species generation

Calculating fire growth and the amount of heat evolved from the primary fire source requires knowledge of the type and amount of fuel involved. Burning rates can be estimated on the basis of data from small-scale tests or by interpolating the results of large-scale tests. For example, the heat evolved can be calculated if the area of a liquid spill is known. If the amount of liquid is known, the time to burn-out can be calculated.

Fire growth information for solids and other burning objects is available from several sources. Heat release rates for many items of furniture, curtains and different types of material are available, and the results can be used to estimate the heat release rates of items in the same category. Correlations are available, e.g. to estimate the effect of mass and other factors on the peak burning rates of furniture. Relevant input information is also available for many other processes of fire development as discussed in 6.2.

Computer programmes with material databases are also available to assist the user in choosing an appropriate heat release rate curve. There are also user-friendly computer programmes with collections of routines based on analytical equations. These include expressions for mass flow through openings, the buoyant pressure of hot gases, species concentrations, flame sizes and room temperatures.

For fully developed fires in small rooms, parametric temperature-time curves have been developed[5],[30]. These curves need as inputs the opening factor and the thermal inertia of the bounding walls.

7.3 Computer models

Zone and field models — described in more detail in ISO/TR 13387-5 — can be used to simulate fire development and species generation, but their main application is in the evaluation of the consequences of fire. A limited number of submodels have been included in some of the zone models to calculate e.g. the spread of fire on a horizontal surface like a mattress or the burning of a wood crib. Usually, however, the development of the fire has to be given as an input.

Research organisations are developing methods which allow the development of a fire to be simulated in a more flexible way. For example, there are ongoing efforts to include flame spread in the CFD models. These models are still at the research stage and can be used for engineering purposes usually by the developers of the models only.

Deterministic models, implemented also as computer codes, describing fire growth in a specific scenario are available. For example, there are several models which simulate fire growth in the standard room/corner test