TECHNICAL REPORT

ISO/TR 11696-1

First edition
1999-12-15

Uses of reaction to fire test results —

Part 1:
Application of test results to predict fire performance of internal linings and other building products

Utilisation des résultats des essais de réaction au feu —

Partie 1: Application des résultats à la prédiction de la performance au feu des revêtements intérieurs et d'autres produits de bâtiment

Reference number
ISO/TR 11696-1:1999(E)

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Foreword

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ISO/TR 11696-1, was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 1, *Fire initiation and growth*.

ISO/TR 11696 consists of the following parts, under the general title *Uses of reaction to fire test results*:

— *Part 1: Application of test results to predict fire performance of internal linings and other building products*

— *Part 2: Fire hazard assessment of construction products*

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Introduction

This Technical Report deals with a methodology for describing fire development from building products in fire rooms under real life conditions by the use of results from small-scale tests, mostly those described in ISO/TR 3814, as input for different types of fire models.

Fire is a complex phenomenon. Its behaviour depends upon a number of inter-related factors. The behaviour of materials and products depends upon the characteristics of the fire, the end-use application and the environment in which they are exposed. The tests described in ISO/TR 3814 provide the basis for obtaining important physical data describing ignition, flame spread, rate of heat release and smoke. Each single test explained in this Technical Report deals only with a simple representation of a particular aspect of the potential fire situation and cannot alone provide any direct guidance on behaviour or safety in fire.

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Uses of reaction to fire test results —

Part 1: Application of test results to predict fire performance of internal linings and other building products

1 Scope

This Technical Report describes how information on basic values for ignition, spread of flame, rate of heat release and smoke can be used in fire growth models for internal linings and other building products to describe the fire hazard in a limited number of scenarios starting with fire development in a small room. Other scenarios include fire spread in a large compartment and fire propagation down a corridor.

The types of models to be used are:

a) mathematical models based on fire growth physics, which calculate fire room variables, the results of which may be used for fire safety engineering purposes; and

b) generalized engineering calculations.

Sub-models can be included within the above models, provided the consistency of the whole is not prejudiced.

The models in general are not limited to one fire scenario.

The models should be used to calculate and describe the fire properties of building products in their end-use conditions. The use of models should not be limited by difficult materials, but it is recognized that some products may not be capable of being modelled (for example due to their complex assembly or to their thermoplastic properties).

Input parameters for models are based on ISO tests, mainly those in ISO/TR 3814.

The quality of a fire model for wall and ceiling linings is assessed by comparison with test results from a full-scale small room test for surface products and by sensitivity analysis on the model itself.

2 References

ISO/IEC Guide 52, *Glossary of fire terms and definitions*.

ISO 3261, *Fire tests — Vocabulary*.

ISO/TR 3814, *Tests for measuring "reaction-to-fire" of building materials — Their development and application*.

ISO 5657, *Reaction to fire tests — Ignitability of building products using a radiant heat source*.

ISO/TR 5658-1, *Reaction to fire tests — Spread of flame — Part 1: Guidance on flame spread.*

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ISO 5658-2, *Reaction to fire tests — Spread of flame — Part 2: Lateral spread on building products in vertical configuration.*

ISO 5660-1, *Reaction to fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (Cone calorimeter method).*

ISO 5660-2, *Reaction to fire tests — Heat release, smoke production and mass loss rate from building products — Part 2: Smoke production rate (dynamic measurement).*

ISO 5725-1, *Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions.*

ISO 5725-2, *Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method.*

ISO/TR 5924, *Fire tests — Reaction to fire — Smoke generated by building products (dual-chamber test).*

ISO/TR 9122-1, *Toxicity testing of fire effluents — Part 1: General.*

ISO/TR 9122-2, *Toxicity testing of fire effluents — Part 2: Guidelines for biological assays to determine the acute inhalation toxicity of fire effluents (basic principles, criteria and methodology).*

ISO/TR 9122-3, *Toxicity testing of fire effluents — Part 3: Methods for the analysis of gases and vapours in fire effluents.*

ISO/TR 9122-4, *Toxicity testing of fire effluents — Part 4: The fire model (furnaces and combustion apparatus used in small-scale testing).*

ISO/TR 9122-5, *Toxicity testing of fire effluents — Part 5: Prediction of toxic effects of fire effluents.*

ISO/TR 9122-6, *Toxicity testing of fire effluents — Part 6: Guidance for regulators and specifiers on the assessment of toxic hazards in fires in buildings and transport.*

ISO 9239-1, *Reaction to fire tests — Part 1: Determination of the burning behaviour with a radiant heat source.*

ISO 9239-2, *Reaction to fire tests — Horizontal surface spread of flame on floor coverings — Part 2: Flame spread at higher heat flux levels.*

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

ISO/TR 11925-1, *Reaction to fire tests — Ignitability of building products subjected to direct impingement of flame — Part 1: Guidance on ignitability.*

ISO/TR 14696, *Reaction to fire tests — Determination of fire parameters of materials, products and assemblies using an intermediate-scale heat release calorimeter (ICAL).*

3 Terms and definitions

For the purposes of this part of ISO TR 11696, the terms and definitions given in ISO/IEC Guide 52 and ISO 3261 apply.

4 Fire scenarios

4.1 There is a need to improve preventive fire protection because of public demand for more safety against fire hazards which have increased during the last decade.

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4.2 To evaluate the fire hazard, technical fire tests have to be used. Since these will provide the basis for safety requirements they must be relevant to the end use of a product.

4.3 Fire growth, smoke production and generation of toxicants or corrosive gas depend on the specific properties of a material, its mass, its form and orientation and its surface area.

4.4 To start a fire and for fire development, three components are necessary: heat, air and combustible material (see Figure 1).

4.5 The development of fire can be split into different phases (see Figure 2, which describes two different fire growth courses).

4.6 Traditionally, fire types in rooms have been subdivided into combustion categories, as is done in ISO/TR 9122 (all parts). This scheme suggests that there are six different fire types, each with a characteristic value of oxygen concentration, CO_2/CO ratio, etc.

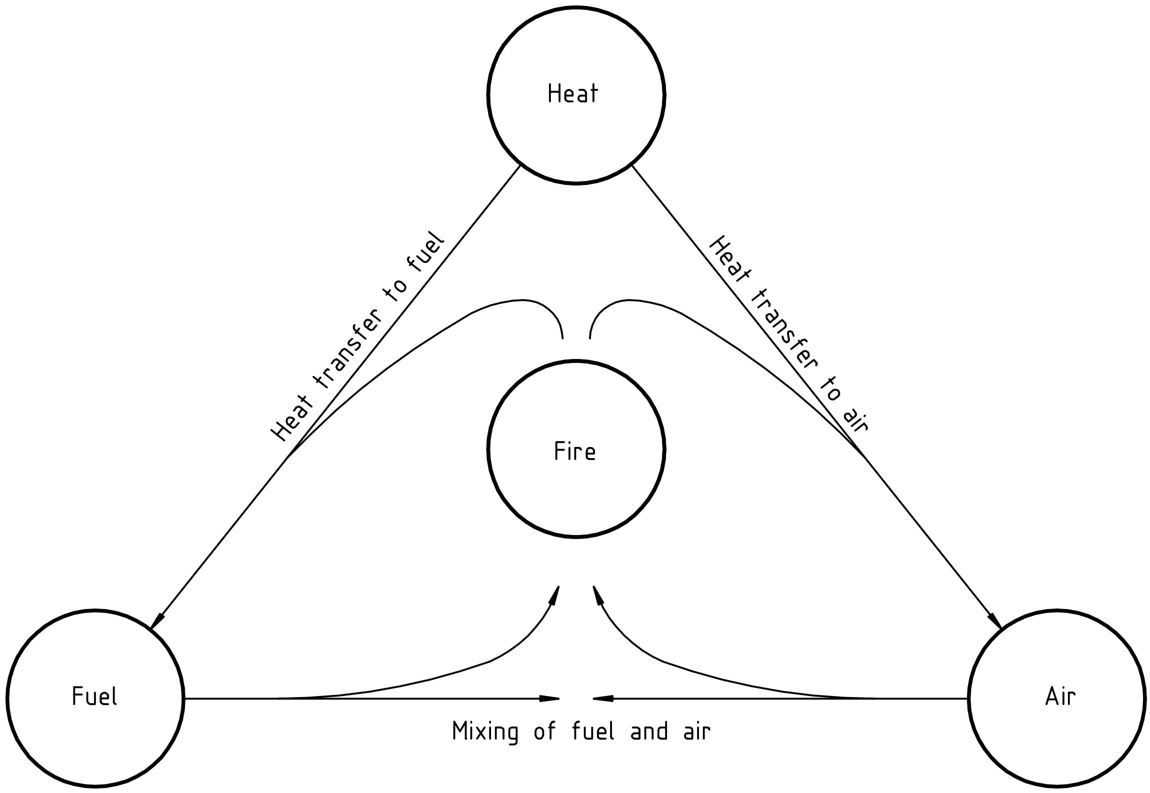

Figure 1 — Components necessary for starting a fire

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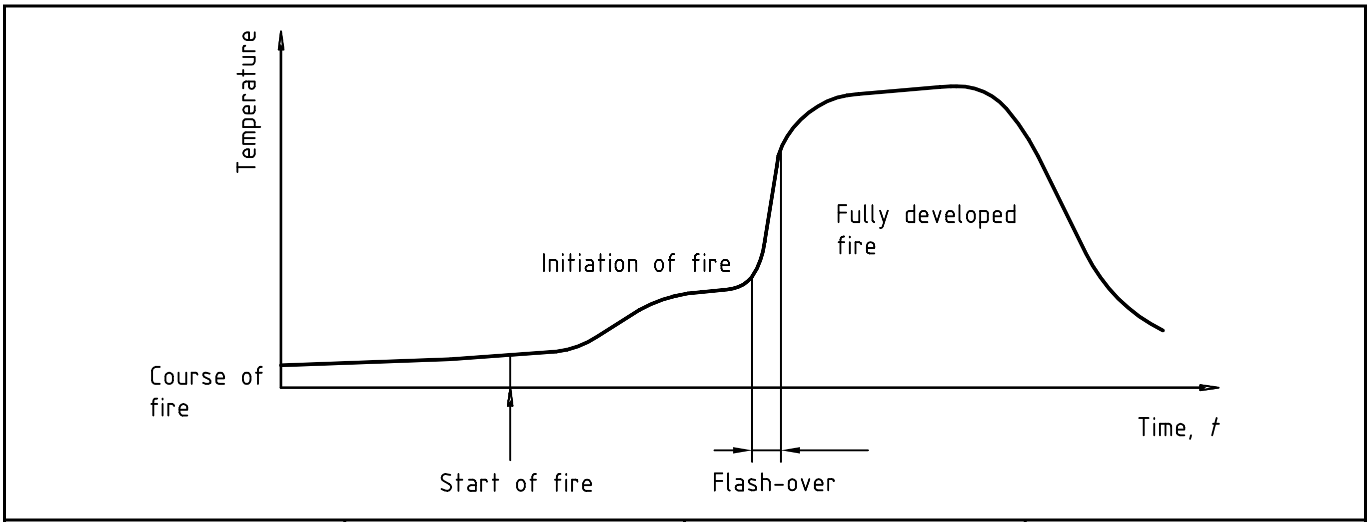

<table>
<tr><td rowspan="3">Hazard</td><td colspan="4">Ignition</td><td colspan="4">Spread of flame</td><td colspan="4">Fire spread</td></tr>
<tr><td colspan="12">Heat release</td></tr>
<tr><td colspan="3">Visibility</td><td colspan="3">Irritation</td><td colspan="3">Toxicity</td><td colspan="3">Corrosivity</td></tr>
</table>

Figure 2 — Fire growth course

5 Experimental methods and their limitations

5.1 Generally, fire tests do not simulate all aspects of a real fire. No single test result can reflect all aspects of each phase in a developing fire.

5.2 Small-scale tests may simulate some aspects of fire growth of real fires. There is a need for wide experience of using test data from such tests and a recognition of difficulty of interpretation with respect to the behaviour of products under real fire situations.

5.3 In general, ISO/TC 92/SC 1 tests can be used if they give physically-based test results which yield parameters relevant to the model employed. Preferably, tests included in ISO/TR 3814 should be used.

5.4 One aim of using small-scale fire tests is to provide data for predicting full-scale fire behaviour of building products.

5.5 Small-scale tests for smoke development, production of toxicants and corrosive gases from building products are under development. There is a need for development of a hazard model using test results of small-scale tests.

5.6 For reasons of cost and practicality, bench-scale tests are normally used for measuring fire properties. The results from a bench-scale test can occasionally be used directly to predict real-scale fire performance. More commonly, the use of some form of fire model is needed to relate the bench-scale test results to expected real-scale fire performance. This is because bench-scale engineering tests endeavour to quantify a material fire property. The performance in the real-scale fire, however, is not necessarily simply or linearly proportional to the underlying material fire properties; this makes the use of some mathematical treatment often necessary.

5.7 Another issue when trying to predict full-scale performance from bench-scale testing is that there is not just one possible full-scale fire scenario. Often, equally plausible fire scenarios can lead to significantly different numeric results. A bench-scale test prediction cannot equally closely conform to two such different full-scale scenarios.

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There is a number of physical apparatus-related issues in bench-scale specimen testing. The results can be influenced by:

a) melting, shrinking, slumping and dripping;

b) intumescence;

c) spalling;

d) charring of products;

e) reflective coating;

f) thermal conductivity of facings.

The following test conditions can influence the result:

1) substrate;

2) holder frame;

3) ignition source;

4) orientation of specimen (direction of flame spread);

5) end-use condition of product, for example joints, fixings and adhesives;

6) air gaps;

7) roughness of surface;

8) effects of geometry;

9) ventilation.

Some of these features can often make it difficult to interpret the results and there is a need to recognize the difficulty of representing this in small-scale tests. Clear guidance for testing procedure and interpretation are needed to obtain valid results. Specialist tests may be needed for certain "difficult-to-test" products, for example ISO/TC 61/SC 4 has developed tests for thermoplastics. ISO/TC 92/SC 1 has developed intermediate and large-scale tests for composites.

5.8 The most important parameters for fire growth process measurements are:

a) ignitability;

b) flame spread rate;

c) heat release rate;

d) smoke production rate.

Effort should be made to use thermal exposures which relate to some real fire situation, preferably to one that will also give results which can be used for fire modelling calculations.

The following four sections of this technical report examine each of the above phenomena in terms of their contribution to the hazard of fire growth, the variables that control these processes and the apparatus or techniques available for measuring the required properties. The motivation for these phenomenological statements is to provide a basis for predicting the fire performance of building products in terms of engineering formulae and material test data. Each section reflects the state of the art and is oriented to allow for continual scientific improvement.

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6 Ignitability

6.1 Introduction

In assessing the fire performance of a building product, it is essential to know under what conditions and how quickly the product ignites. Such information is needed to predict the onset of flaming combustion of the first item or area ignited at the initiation of a fire. In addition, the information is an important element in the calculation of fire spread to other parts of a room or compartment, either due to remote ignition of objects or due to flame spread over surfaces. The propensity for ignition is characterized by a number of material properties which can be calculated from bench-scale ignition data on the basis of a mathematical model of the ignitability test. The resulting properties can then be used to predict ignition under real fire conditions, provided these conditions are known or estimated via a computer fire model or other means. This section describes the ignition phenomenon in a bench-scale test, the material properties related to ignition, procedures to calculate these properties from ignition test data, and the use of these properties in assessing the fire performance of building products.

6.2 Ignition theory and related material properties

When a material is exposed in a fire, a major part of the incident heat flux is conducted into the material. This conduction results in a temperature rise of the material, with a maximum at the exposed surface. The temperature profile in the material is a function of the magnitude of the absorbed heat flux and how this flux varies with time. After being exposed for some time, the surface temperature may reach a critical level at which the material starts to decompose and release combustible volatiles. The volatiles mix with the surrounding gases. If this mixture is flammable and if the gas phase temperature, at least locally, is sufficiently high, flaming ignition will result.

From the above description of the piloted ignition phenomenon, it is obvious that detailed ignition models consist of a number of equations describing heat and mass transfer in the solid and gas phase. Such models are too complex and are not very useful for analysing ignition test data in terms of the material properties that are needed for predicting fire performance. A number of simplified ignition models have been developed, and have been used with great success. The guidelines in this section are based on such a simplified model.

The model is based on two major assumptions. First, a critical surface temperature, T_{ig}, is used as the criterion for ignition. T_{ig} is primarily a material property, but its value also depends on the mode of ignition, piloted or unpiloted. Second, it is assumed that the material behaves as an inert solid, and pyrolysis effects prior to ignition are negligible. Strictly speaking, these assumptions are not always valid. However, experience has shown that these assumptions are reasonable for an engineering analysis.

A thermal model as conceptually outlined above, applied to a bench-scale ignition test, is described in detail in 6.3. The model assumes that ignition tests are conducted under exposure to radiant heat, in the presence of a pilot flame. This is consistent with ISO/TC 92 ignition test methods (see 6.6). The solution of the model equations leads to a method for correlating piloted ignition data. These data generally consist of ignition time t_{ig}, measured over a range of irradiance levels, $\dot{q}''_e$. The correlation can be used to obtain the following material properties:

$\dot{q}''_{cr}$ = critical irradiance for piloted ignition (kW/m^2),

$\dot{q}''_{min}$ = minimum irradiance for piloted ignition (kW/m^2),

T_{ig} = surface temperature at piloted ignition (°C or K), and

$k\rho c$ = apparent thermal inertia (kJ^2·m^{-4}·K^{-2}·s).

The critical irradiance, $\dot{q}''_{cr}$, is the heat flux level for which the model predicts $t_{ig} \rightarrow \infty$. Since $\dot{q}''_{cr}$ is a function of not only T_{ig} but also of the surface heat transfer characteristics in the ignition test, it is a model parameter rather than a material property. The minimum irradiance $\dot{q}''_{min}$, is the highest heat flux level below which piloted ignition under practical conditions does not occur. Often, but not always, $\dot{q}''_{cr}$ is a reasonable estimate for $\dot{q}''_{min}$.

The material properties that result from an analysis of bench-scale ignition data can generally be used to predict ignition performance under fire conditions and configurations that are different from those in the bench-scale test. For example, the properties needed to predict ignition of a material under flaming exposure are identical to those

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that can be obtained from ignition tests under radiant exposure. Annex A gives a practical example to illustrate the procedure for calculating material properties from piloted ignition data, and the use of these properties to estimate ignitability under room fire exposure conditions.

6.3 Procedures for calculating material properties from ignition test data

A schematic illustration of a thermal model for a slab of a material exposed in a bench-scale ignition test is shown in Figure 3. It is assumed that L is sufficiently thick so that the material behaves as a semi-infinite solid. Only a fraction, equal to emissivity ε of the incident irradiance $\dot{q}''_{e}$ is absorbed by the solid. Heat losses from the surface are partly radiative and partly convective, with $h_{c} \approx 10\ \text{W·m}^{-2}\text{·K}^{-1}$ to $15\ \text{W·m}^{-2}\text{·K}^{-1}$ typical for bench-scale ignition tests. The ignition time t_{ig}, is the time needed for the surface temperature to reach $T_{s} = T_{ig}$. It is further assumed that the material behaves as an inert solid. Thus, the problem is reduced to a one-dimensional heat conduction problem with non-linear boundary conditions.

Extensive numerical solutions of the heat conduction over a wide range of values for $\dot{q}''_{e}$, T_{ig}, and thermal properties (constant k and c, as well as linear functions of temperature) by Janssens [47] resulted in the following functional relationship between $\dot{q}''_{e}$ and t_{ig}[1]:

$$\dot{q}''_{e} = \dot{q}''_{cr}\left[1 + 0{,}73\left(\frac{k\rho c}{h_{ig}{}^{2}t_{ig}}\right)^{0{,}55}\right] \qquad (1)$$

where the steady surface heat transfer coefficient at ignition h_{ig}, is given by:

$$\varepsilon\dot{q}''_{cr} = h_{c}(T_{ig} - T_{\infty}) + \varepsilon\sigma\left(T_{ig}^{4} - T_{\infty}^{4}\right) \equiv h_{ig}(T_{ig} - T_{\infty}) \qquad (2)$$

Equation (1) suggests plotting $(1/t_{ig})^{0{,}55}$ as a function of $\dot{q}''_{e}$. The critical irradiance, $\dot{q}''_{cr}$ is then obtained as the intercept of a straight-line fit through the data points and the abscissa. T_{ig} and h_{ig} are calculated from $\dot{q}''_{cr}$ via equation (2). Finally, an apparent thermal inertia is calculated from the slope of the straight-line fit via equation (1).

A slightly inferior fit to Janssens's solutions is given by:

$$\dot{q}''_{e} = \dot{q}''_{cr}\left[1 + 0{,}71\left(\frac{k\rho c}{h_{ig}^{2}\, t_{ig}}\right)^{0{,}5}\right] \qquad (3)$$

Although this equation is slightly less accurate than equation (1), the 0,5 power is consistent with many other investigators who have proposed functional forms for correlating piloted ignition data. Both equations (1) and (3) are valid for thick solids only.

Mikkola and Wichman [48] analysed the thermal ignition model in two ways:

a) exact solution via Laplace transforms of the linearized problem for thermally thick and thermally thin specimens, and

b) approximate integral solution of the problem with non-linear heat losses for thermally thick, thermally thin and thermally intermediate specimens.

Both approaches resulted in the same recommendation i.e. to correlate $(1/t_{ig})^{n}$ with $\dot{q}''_{e}$ where $n = 0{,}5$ for thermally thick materials, $n = 1$ for thermally thin materials and $n = 0{,}6$ for thicknesses in between. Some guidance was given on how to estimate thermal thickness from physical thickness for wood products: thermally thick specimens are over 20 mm, thermally thin specimens are thinner than 1 mm, while $n = 0{,}7$ corresponds to a thickness around

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[1] In reference [47] the value of the exponent was 0,547. Since this gives a false sense of precision, it is rounded here to 0,55 for correlating piloted ignition data. Both equations (1) and (3) are valid for thick solids only.

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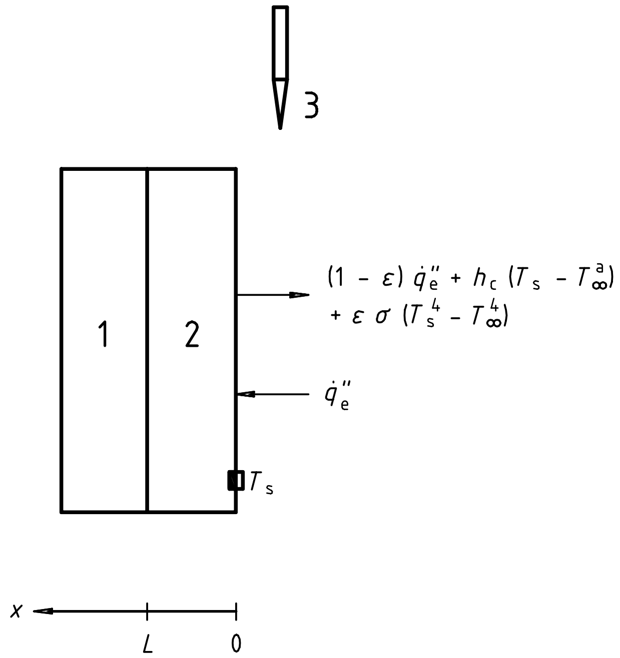
5 mm. Practical application of this procedure was illustrated for some data from previous investigators and new data for a few wood species, PMMA and some other materials.



Key

1 Backing board

2 Specimen

3 Pilot flame

a Ambient temperature T_∞

Figure 3 — Thermal model for a slab of a material exposed in a bench-scale ignition test

6.4 Factors affecting ignitability0,7

Irradiance is the main factor affecting the time to piloted ignition. A minimum irradiance level is required for piloted ignition to occur in the first place. However, there is a number of other factors affecting piloted ignition. Some of these factors are related to the experimental conditions, others are associated with the material characteristics and properties. Janssens [10] provides an extensive discussion of these factors. Various factors are listed below.

a) Experimental conditions:

 1) air flow around the specimen;

 2) orientation of the specimen;

 3) specimen size;

 4) pilot size and location;

 5) spectral distribution of the source.

b) Material conditions and properties:

 1) moisture;

 2) surface absorptivity and emissivity;

 3) diathermancy;

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4) specimen thickness;

5) surface coating.

6.5 Use of ignition properties to predict fire performance

Material properties obtained via procedures outlined in 6.3 can be used directly to predict ignition performance of materials under real fire conditions. However, these real fire conditions must be known or must be estimated from test data or via a computer fire model. In addition, the submodel that calculates the response of the material to this exposure must be expanded and modified from the model outlined in 6.3. This is necessary to account for possible differences of the major heat transfer modes (flame versus heater radiation, convective gains instead of losses etc.), and the fact that real fire exposures vary with time.

6.6 Experimental methods

6.6.1 Experimental methods in common use

Radiative and convective heat exposure methods as well as flame impingement methods are used to measure ignitability. The discussion in this clause is limited to radiant exposure methods. Such methods are most suitable for the purpose of deriving material properties for prediction of ignition performance in real fires.

Three methods may be used for measuring ignitability of building products: the radiant heat ignitability test ISO 5657, the cone calorimeter ISO 5660-1, and the LIFT apparatus ASTM E1321. The first two methods utilize a conical electrical heater to produce a constant uniform heat flux to the specimen. The third method comprises a radiant gas panel.

The main differences between the three methods are specimen size and orientation, backing material, type of pilot, and ventilation near the specimen. The type of heater is perhaps the most important difference between ASTM E1321 and the other two methods. In spite of these differences, the thermal theory outlined in 6.3 is applicable to all three methods. The model accounts for differences between the test methods by assigning a slightly different value to convection heat transfer coefficient, h_c. Consequently, the measured ignition times are slightly different from one method to another, but the resulting material properties are very much the same.

6.6.2 Comparison between experimental methods

A detailed study comparing test results from the ISO 5657 ignitability test and the ISO 5660-1 cone calorimeter resulted in the following relationship between ignition time measured at the same irradiance level in the cone calorimeter ($t_{ig,5660}$) and in the ignitability test ($t_{ig,5657}$) [11].

$$\left(\frac{t_{ig,5660}}{t_{ig,5657}}\right)^{-n} = 0{,}86$$

where n equals 1, 0,6 or 0,5 for thermally thin, intermediate or thick cases.

Other studies comparing the same methods concluded ignition times are similar, provided cone calorimeter data are obtained for the horizontal specimen orientation [12], [21].

6.6.3 Repeatability and reproducibility

A number of round robin exercises has been conducted with the three methods discussed in 6.6.1. An analysis of combined ASTM and ISO round robin data with the cone calorimeter resulted in the following equations for repeatability r, and reproducibility R, of t_{ig} in the range of 5 s to 150 s.

$$r = 4{,}1 + 0{,}125\ t_{ig}$$

$$R = 7{,}4 + 0{,}220\ t_{ig}.$$

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A round robin exercise with the ISO 5657 ignitability test resulted in:

$r = 2{,}9 + 0{,}241\ t_{ig}$

$R = 2{,}2 + 0{,}458\ t_{ig}$.

An analysis of ISO round robin data from six laboratories on six materials tested according to ASTM E1321 resulted in a relative standard deviation over all laboratories between 3 % and 12 % for T_{ig}, and between 12 % and 77 % for $k\rho c$.

6.7 Conclusions on ignitability

Several standard test methods are available for measuring time to piloted ignition over a range of irradiance levels. Despite differences in specimen size, orientation, backing materials, type of pilot, etc. all methods yield similar results. Material properties that are needed to predict ignition performance in real fires can be obtained from the bench-scale measurements via correlations that are based on a simple thermal theory. This model can account for the differences between the various test methods. Consequently, comparable thermal property values are obtained regardless of the apparatus that is used for generating the ignition data.

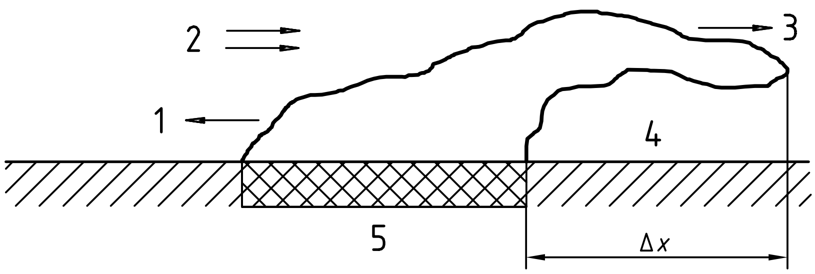
7 Flame spread

7.1 General

Processes of flame spread in general depend on orientation of the surface, the direction of spread relative to air flow (wind) and fuel properties. Although there is not a universal formula for flame spread, rate of spread (v) can be represented in terms of the distance (Δx) over which the advancing flame must heat the solid to its ignition temperature in the time period, t_{ig} (see Figure 4). Thus,

$$v = \frac{\Delta x}{t_{ig}} \tag{4}$$

Various theoretical models have been proposed which give the underlying variables for Δx and t_{ig} in equation (4) for many modes of flame spread, for example upward, downward, wind-aided, wind-opposed flow [23]. In addition to the rate at which flames spread across a surface, it is also necessary to demonstrate whether flame propagation occurs away from the initial seat of the fire. A number of materials will not propagate a flame under normal ambient conditions and pre-heating of the surface is usually required to enable spread to occur. Hence, the rate of spread and the conditions required to permit spread are two significant factors for characterizing flame spread.



Key

1 Wind – opposed flow spread

2 Air flow

3 Wind – aided spread

4 Flame front

5 Combustion zone

Figure 4 — Flame spread model

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7.2 Contribution of flame spread to fire growth hazard

Fire can harm people or structures by the production of energy and effluent which correspondingly raise the temperature and concentration levels of noxious species within the fire room. This production rate $\dot{P}$ is directly related to the area A of fuel burning by the following equation:

$$\dot{P} = \dot{P}'' \times A \quad (5)$$

where $\dot{P}''$ is the production rate per unit area of mass, energy or species. The quantity $\dot{P}''$ is measurable (for example, ISO 5660-1 cone calorimeter), and for a given material it depends on the imposed environmental conditions and time. Predictive methods are being developed for the mass loss rate of fuel per unit area from which $\dot{P}''$ can be determined from chemical properties (for example the heat of combustion). Fire growth hazard can then be quantified in terms of $\dot{P}$ for a given scenario (for example small room, large room).

For a specific room, a major hazard can be represented by flashover which marks the transition to full room involvement. Following flashover, all of the room combustibles become involved, and for most situations the fire will be ventilation-controlled. The nature and size of $\dot{P}$ and $\dot{P}''$ will markedly change since these are no longer attributable to a single fuel and can be strongly affected by the limited air supply. Flashover is a principal critical limit state in fire growth.

For a specific room, flashover can be determined by the attainment of a critical energy release rate. The area A is a direct result of flame spread and the burn time. In general, the contribution of flame spread to fire growth hazard may be expressed by a critical value for $\dot{P}$, although it must be remembered that flashover may not be likely in many large rooms.

7.3 Flame spread relationships

7.3.1 General

It has often been noted that fire growth proceeds exponentially, at least for some period of time. This growth is usually associated with wind-aided flame spread. In such cases, the increase in ignited area, dA can be proportional to the ignited area A. Over time, this type of proportionality causes an exponential growth rate. Wind-opposed flame spread is usually much slower. Here, the driving force for flame spread is more or less constant and is not dependent on the size of the area already burning. There can be some acceleration of wind-opposed flame spread rates with time, however. This acceleration is due to the solid material being progressively raised to a higher temperature, not due to a larger area of flames upon surfaces. There is not much systematic information on the heat fluxes from flames that drive wind-opposed flame spread processes. It is known that the flame fluxes are geometry-dependent. For vertical specimens, lateral or downward flame spread involves thin, boundary layer flames. For wind-opposed flame spread on horizontal, face-up specimens large pool-fire type of flames can provide substantial radiant heating (see ISO 5658-1, ISO 9705 and ISO 11925-1).

7.3.2 Heat fluxes, wind-aided spread

Considerable data are available on heat fluxes from flames in wind-aided flame spread, especially for vertically oriented specimens in buoyancy-driven flows. Some data also exist where the specimen is horizontally oriented and the flow velocity is produced by mechanical means. The former orientation is far more common for building fire safety, and some experimental results for this case are discussed below.

Heat fluxes from the flame to the surface are characteristically uniform over the ignited region. Beyond the region where the surface is ignited (i.e. where the flames are no longer "attached"), the flux drop-off distance can be in the order of metres. The actual drop-off distance is understood to depend mainly on the flame height, which, in turn, is determined by the heat release rate. Summaries of significant amounts of experimental data have been published by Hasemi [29] and Quintiere [30].

The heat fluxes in the "attached" region are typically from 25 kW/m^2 to 45 kW/m^2 when only a burning wall is considered. When the burning wall is augmented by an additional fire source, for example a burner, values up to 80 kW/m^2 can be recorded. The heat fluxes downstream of the attached region have a maximum of 25 kW/m^2 to 45 kW/m^2 [30], [31] and drop to lower values further downstream.

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Heat fluxes on walls in the wind-aided scenario where burners are used have been studied by Kokkala [40]. These were typically around 40 kW/m^2 where burners with smaller size face openings were used, going up to 80 kW/m^2 for larger burners. Williamson et al. [32] report values of 50 kW/m^2 to 60 kW/m^2 for the common scenario of a 150 kW burner having face dimensions of 0,3 m by 0,3 m and being located in the room corner.

7.3.3 Heat fluxes, wind-opposed spread

Existing experimental data on flame fluxes in wind-opposed flame spread scenarios are both sparse and inconsistent. In general, peak values of 20 kW/m^2 to 80 kW/m^2 have been reported. The heat flux to a specimen ahead of the flame front can be in order of 20 kW/m^2 to 80 kW/m^2. This heat flux drops off to almost zero over a very small distance (in the order of several mm) in the case of wind-opposed spread. For the pool-like flames over horizontal surfaces, approximately 5 mm may be a typical drop-off distance, although existing measurements do not offer reliable guidance.

There are difficulties in relating bench-scale flame spread measurements to real-scale fires, since very little information is available about wind-opposed flame fluxes in real-scale fires. For one material studied (PMMA) in the horizontal, face-up configuration, flame spread rates were seen to increase with specimen width, but less than linearly. Validation of bench-scale flame spread measurements against real-scale fires still has to be done on a detailed level; the existing comparisons address the overall fire predictions, not the flame front spread rates and flame front flux values.

7.4 Test equipment and experimental methods

Many standard test methods exist that measure the flame spread characteristics of materials (ISO 5658-2, ISO 9239-2, ISO 9705). Most give a measure of performance in terms of distance burned or rate of spread. Some operate in a wind-aided mode, and some utilize external radiant heating to promote wind-opposed flame spread.

None of these methods permits a generalization of flame spread results in terms of engineering formulae. In contrast, some test methods can now supply data for such formulae; for example the cone calorimeter can measure the $\dot{P}''$ values of equation (5) for many simple materials. In particular, the rate of energy release per unit area can be measured as a necessary variable in formulating Δx for wind-aided spread. The major limitation in this process is the use of cone calorimeter data at one burning condition to represent different burning conditions in the flame spread process. This limitation should diminish as scientific modelling improves and this information may be more accurately translated. In addition, the formulation of expressions for Δx should also improve.

Other needed data, such as t_{ig} under fixed heating conditions, are available from various procedures with little direct dependence on the apparatus [10]. Its associated analysis procedure has shown that flame spread theory can be used to correlate material data and predict fundamental properties. This method can even determine the minimum temperature for spread, but a practical means does not yet exist to calculate this property for wind-aided spread. Thus, ISO apparatus and procedures are now available, to supply data to flame spread formulae to permit the estimation of flame spread rates for many construction products. The application of this process will be extended as additional flame spread procedures (for example for horizontal flame spread over floor coverings) are developed. ISO/TC 92/SC 1/WG 3 is pursuing the development of data for the precision of spread of flame methods.

7.5 Conclusions on flame spread

One apparatus is probably not able to supply all the necessary data for flame spread, and so data from more than one test are necessary to reflect different flame spread modes.

Flame spread should be classed by scenario and configuration at least to the extent of distinguishing between the modes of wind-aided and wind-opposed spread. For example, ceiling coverings would generally be subject to wind-aided spread while floor coverings may be subject to either wind-opposed spread or wind-aided spread depending on the ventilation into the fire room.

Guidance should be given for linking test data to flame spread formulae and the limitations discussed.

Special consideration should be given to flame spread with materials which show unusual thermal properties, for example thermoplastics which shrink, slump, melt or drip away from applied heat sources.

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8 Heat release rate

8.1 General

The rate of heat release from building materials has been considered as an important property in describing their fire hazard for several decades. Standard procedures have been applied in many countries and several other approaches have been developed for research purposes. However, other techniques, mainly based on temperature measurements, may not be as accurate in describing the fire behaviour of new types of building products. New techniques based on oxygen consumption measurements are more meaningful [8].

The contribution of rate of heat release to the fire growth hazard has been quite self evident to both researchers and building authorities. It has mainly been applied to wall and ceiling linings and more recently also to furniture and goods stored in rooms. The fire hazard can be defined as the time to flashover in a room or a certain temperature in the upper hot gas layer. During recent years, models have been developed which describe relationships between results from testing in small scale and in room scale.

8.2 Variables determined

Heat is generated when vapours released from materials are burnt in air. Those combustion reactions are exothermic. The heat released per mass of material burnt is quite different for different materials and fuels, but expressed per mass of oxygen consumed, it is fairly constant, 13,1 kJ/g, usually within ± 5 % for most materials [14]. This fact forms the basis for the oxygen consumption technique now extensively used in fire testing. The basic equation used can be written

$$\text{RHR} = E\left(X_{\text{O}_2}^0 - X_{\text{O}_2}\right) d_{\text{O}_2} \times V \tag{6}$$

where

RHR is the rate of heat release (MW);

E is the heat produced per mass of oxygen consumed (= 13,1 kJ/g);

X_{O_2} is the volume fraction of oxygen in exhaust duct;

$X_{\text{O}_2}^0$ is the volume fraction of oxygen, initially;

d_{O_2} is the density of oxygen (kg/m^3);

V is the volume flow of gases in exhaust duct (m^3/s).

More precise equations have been developed for various applications [15], [16] and are also given in the different standard test methods.

The rate of heat release, RHR, is often given per unit area (kW/m^2) when tested in small scale but as an overall rate (kW) when tested in larger scale, since there is a progressive involvement of specimen area in the latter case.

RHR is usually expressed as a function of time and such plots often exhibit one or more peaks. If a single value is desirable, a peak value or an average value over a certain period of time may be chosen. However, peak values should be used with great care, since many materials exhibit narrow peaks, for which the maximum rate depends on the time interval between recordings and the response time of the analysers. An average around the peak is preferable. The total heat release (MJ and MJ/m^2) for the burning period, or parts of it, can also be used. The best approach is to use the entire heat release curve including ignition time to extract as much information as possible.

8.3 Factors affecting rate of heat release

The rate of heat release obtained by the oxygen consumption technique is a basic property which can be determined independently of measuring technique or apparatus design. However, some factors will affect the rate

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of heat release. These factors are heat flux level, scale (specimen size) and orientation. The influence of these factors is not very strong and mainly observed in the rate of heat release. In integrated data, the influence will more or less disappear, for example the effective heat of combustion and the total heat release during a defined burning period are quite constant.

Some formulae have been derived for wood products [16], but they can also be applied more generally:

$$Q = H_c\, m \tag{7}$$

$$m = q_n / \left[C\left(T_p - T_o\right) + L_v \right] \tag{8}$$

where

H_c is the heat of combustion;

m is the mass loss rate;

q_n is the net heat flux to the material at the pyrolysis front;

C is the specific heat capacity;

T_p is the pyrolysis temperature;

T_o is the initial temperature;

L_v is the heat of gasification.

Equations (7) and (8) can be combined with:

$$Q = H_c q_n / \left[C\left(T_p - T_o\right) + L_v \right] \tag{9}$$

In such relationships, moisture effects can be included in C and L_v.

Equation (9) shows that for some products only q_n changes when the external heat flux is changed. Note also that the net heat flux q_n is not necessarily linearly dependent on the external heat flux.

Other material data like density and related properties such as thermal conductivity and specific heat, often expressed as thermal inertia, will also affect the rate of heat release.

The air supply will affect the heat release when studied over a large range of air-to-fuel ratios. The mass loss rate, which is strongly related to rate of heat release, will decrease by about 20 %, when the oxygen concentration decreases from 21 % to 10 % [18]. Other studies [19] indicate a somewhat larger effect.

8.4 Relationships

The relationships between data obtained in small-scale testing and the full-scale fire behaviour are of major interest. Many early attempts have been used to classify materials according to different types of heat release test procedures like the British fire propagation test BS 476-6 and the Nordic hotbox. In the latter case, a full scale scenario ("room and kitchen") was used to define the classification limits. Such systems may work well for traditional building materials, but fail for some new synthetic materials and for some composites. In those cases a large-scale test is required.

The possibility of developing more scientifically based relationships has been emphasized [20] and some early attempts made. Recently, different approaches have been presented with respect to the ISO 9705 room corner test. Some of them are quite simple and empirical but expressed in basic parameters [21]; others are more physical, taking the progressive involvement of new burning areas into account [22] or using a combination of

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several bench-scale data in a numerical solution [23], [24]. These approaches are quite different but are all leading to the same conclusion that rate of heat release determined in small-scale testing is a major factor in calculating the time to flashover in a small room fire scenario. Other scenarios still need careful development work, even for the first stage models.

8.5 Experimental methods

8.5.1 Cone calorimeter

This test method for measuring rate of heat release is described in ISO 5660-1 and was developed during the 1980s. This is the main equipment needed to measure heat release data on a small scale. In addition, time to ignition, mass loss and smoke production can be measured simultaneously.

The equipment consists of a truncated cone of an electrical heating element which can produce irradiance levels up to 100 kW/m^2 at the specimen surface. The specimen (100 mm $\times$ 100 mm $\times$ thickness up to 50 mm) with its holder is placed on a load cell and may be oriented horizontally, facing upwards, or vertically with a mobile spark igniter close to its surface. The combustion products are collected in a hood and a duct with a fan.

Several parameters are measured in the duct as a function of time, for example volume flow rate, temperature and oxygen concentration, and used for calculations of heat release data. The horizontal orientation and the use of an edge retainer frame is recommended for building products.

There are limitations in testing some materials. Those with large surface deviations and/or with joints are most obvious because of the small specimen size. Materials which intumesce or melt are typical examples of troublesome fire behaviour in small-scale testing. Materials which intumesce can be tested at increased cone/specimen separations to reduce the tendency for the intumesced material to contact the spark igniter on the cone heater. Melting materials can be tested in horizontal orientation, even if the heat flux on the surface after melting is decreased. Only correlation studies with full-scale fire behaviour can justify how valid small-scale testing is for such materials.

A round robin exercise has been carried out within ISO/TC 92/SC1/WG 5 and is presented in ISO 5660-1. The repeatability r and the reproducibility R for the total heat release, q_{tot}, in the range from 5 MJ/m^2 to 720 MJ/m^2 was determined according to ISO 5725 (parts 1 and 2) as follows:

$$r = 7{,}4 + 0{,}068\ q_{tot} \quad (10)$$

$$R = 11{,}8 + 0{,}088\ q_{tot} \quad (11)$$

This means that the standard deviation is in the range of 2 % to 8 % for repeatability and 4 % to 12 % for reproducibility except for very low absolute values of heat release where the standard deviations may be higher.

8.5.2 Intermediate scale heat release calorimeter (ICAL)

The ICAL was first developed to measure heat release rate of assemblies, and became an ASTM standard in 1994. It is now in the process of being developed into an ISO standard (see ISO/TR 14696).

In this test method materials, products and assemblies are exposed in vertical orientation to controlled levels of radiant heating. Electrically heated wires are used as the ignition source. Samples are tested in thickness and configurations representative of actual end product or system uses. A 1 350 mm high and 1 542 mm wide natural gas fired radiant panel is used as the heat source.

Time to ignition, heat release rate, mass loss rate and visible smoke development can be measured on 1 m $\times$ 1 m samples exposed to a uniform and constant heat flux of up to 50 kW/m^2 under well-ventilated conditions. Additional fire parameters needed as input in fire models such as surface temperature, ignition temperature, temperature gradients in the specimen and combustion gas yields can be measured.

The heat release rate measuring principle is the same as for the cone calorimeter and room corner test. The same exhaust and measuring equipment that is used for the room corner test can be used for the ICAL.

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Although good repeatability was shown in the test method [50], no reproducibility statement has been developed. A round robin test with four participating laboratories is in the planning stage.

8.5.3 Full-scale room test for surface products

In the full-scale test described in ISO 9705, the measuring principles are the same as in the cone calorimeter, except mass loss is not determined.

The equipment consists of a small room, 2,4 m × 3,6 m with a height of 2,4 m and a door opening in one end. The walls and/or ceiling are covered with the test material and a gas-fired ignition source is placed in one of the inner corners. The combustion products are collected in a hood outside the door and further fed into a duct with a fan.

An initial round robin exercise, with five laboratories participating, has been carried out with four different lining products [25]. The results indicate that the reproducibility of the method is good and typical of other full-scale test methods. The 95 % confidence interval of the mean time to flashover was ± 18 s to ± 37 s for three of the products. Similar ranges were found also for the rates of smoke and CO production. The results for the fourth product varied considerably, most probably because of differences in the methods of gluing the lining to the substrate. Although the results of the test seem to be reasonably reproducible, the method description requires some improvements.

A wider round robin exercise has been carried out as a joint activity between ISO/TC 92/SC 1 and ASTM. The study involved 12 laboratories throughout the world and seven lining products. Only two of these products reached flashover within 20 min. The repeatability r and reproducibility R for the parameter times to reach 1 MW, 750 kW, 600 °C in the room, 600 °C in the door or 20 kW/m^2 at floor level were all 27 % to 33 % for r and 29 % to 41 % for R according to ISO 5725 (parts 1 and 2). Five products did not reach flashover. The repeatability and reproducibility in these cases were 3 % to 85 % for r and 16 % to 100 % for R for total heat release during time periods up to 15 min. The higher values are generally for products with very low absolute heat release.

8.6 Conclusions on heat release

a) Rate of heat release is a major parameter for predicting full-scale fire behaviour.

b) It can be obtained independently of the measuring apparatus by the oxygen consumption technique.

c) The external factors influencing the data are possible to handle.

d) The ISO 5660-1 cone calorimeter is a well-established technique to obtain small-scale data, but some details need clarification.

e) Basic relationships to full-scale room fires are known and predictive models are in development.

f) Further guidance is needed on heat flux levels and on which data should be used for hazard assessment.

9 Smoke production and obscuration

9.1 Theory/variables determined

Smoke is always produced in real fires. Smoke particulates reduce the visibility due to light absorption and scattering. Consequently, people may have difficulties in finding escape routes. A practical and commonly used way to determine visibility is the distance at which an object is no longer visible. Depending on smoke movement, the hazardous area can be large and the expansion of the smoky environment very fast. This clause is based on information in references [26] and [27].

Smoke is basically a product of incomplete combustion. It may be from flaming or smouldering (non-flaming) combustion, each of which can produce quite different types of smoke.

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9.1.1 Smouldering 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. Smoke from smouldering combustion is similar to that obtained from carbon-based materials heated to temperatures at which there is chemical degradation and evolution of volatiles [27]. The particle size of the spherical droplets from smouldering combustion is generally in the order of 1 μm.

9.1.2 Flaming combustion

Smoke from flaming combustion is different in nature and consists almost entirely of solid particles. The particles of the carbon-rich smoke are very irregular in shape. Most of these particles are formed in the gas phase as a result of incomplete combustion and high temperature pyrolysis reactions at low oxygen concentrations [27]. The size of the irregular particles is often much larger than those from the smouldering combustion. The carbonaceous smoke particles in the flames emit radiant energy (as black body emission) which is seen as yellow luminosity.

9.1.3 Basis of smoke measurement units

When making optical smoke measurements, the primary results are usually expressed as an optical density or light extinction coefficient. These two properties are essentially the same, but expressed in different ways mathematically. Both relate the intensity of an incident light beam to the intensity of the transmitted light over a defined path length. In older studies, the base-10 units are used:

$$I/I_0 = 10^{-DL} \qquad (12)$$

where

I is intensity of transmitted light;

I_0 is intensity of incident light;

D is the optical density per metre (m^{-1});

L is path length of beam through smoke (m).

Thus

$$D = -(1/L)\log(I/I_0) \qquad (13)$$

In other variants of base-10 units, also dimensionless optical density $D' = \log(I/I_0)$ has been defined as decibel per metre, i.e. the right hand side of equation (13) multiplied by 10 has been used. Since the laws governing attenuation of radiation through obscuring media are intrinsically expressed in base-e units, the current preference is for

$$I/I_0 = e^{-kL} \qquad (14)$$

where k is the light extinction coefficient (m^{-1}) and thus

$$k = -(1/L)\ln(I/I_0) \qquad (15)$$

The equation between optical density per metre (equation 13) and the extinction coefficient is thus:

$$k = D \ln 10 \qquad (16)$$

Equations (12) and (13) are known as Beer-Lambert's or Bouguer's law, which is valid only for monochromatic light. However, the equations have been widely used also for polychromatic (white) light, even if a certain deviation might be expected.

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The rate of smoke production RSP is of interest in many cases. It is defined as follows:

$$\text{RSP} = c\, V_f \quad (17)$$

where c is either optical density per metre D or extinction coefficient k depending on the base used (10 or e), and V_f is volume flow rate. Using this, the total smoke production TSP can be expressed as:

$$\text{TSP} = \int_0^t \text{RSP}(t)\,dt \quad (18)$$

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

9.2 Factors affecting smoke development and obscuration

The two types of combustion mentioned above may give different smoke yields. For example, it is often observed for wood fires that the amount of smoke is smaller with flaming combustion than with smouldering. For plastics, however, no such generalization can be made. The smoke produced under smouldering conditions can be smaller or bigger than under flaming conditions, depending on the type of plastics.

The smoke production may also depend on the burning environment, not just on what material is being burned. Experimental studies have shown smoke yield to be dependent on variables such as radiant heat flux, oxygen concentration, ventilation, specimen orientation and geometry, and moisture content of specimen. Most of these conditions can also vary between different phases of fire. However, there are two distinct parts to the smoke problem: one relating to the early stages of fire (pre-flashover, with perhaps only a single item involved), and the other relating 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/product producing rather small amounts of smoke per fuel area, may have a large smoke production because of a rapid surface spread of flame. This is especially important when comparing fires (or tests) of different sizes.

9.3 Relationships

There is not much information available in the scientific literature concerning modelling/predictive correlations between small-scale smoke data and real fires/large-scale test results. The reported correlations deal with cone calorimeter and room scale data for linings and surface products [28], [49]. The conclusions of studies of 28 such products in the cone calorimeter (ISO 5660-1) and the room corner test (ISO 9705) are the following. Good correlations for predicting large-scale smoke behaviour have been obtained when using the average rate of smoke production (RSP_{ave}) or total smoke production (TSP) as correlation parameters. However, the predictions seem to be good only for products having long enough time (more than 10 min) to flashover on a large scale, which is essential since some products produce large amounts of smoke even if they do not reach flashover. The total smoke production might even be used for all the reported 28 products as a rough estimate. In [49] there is a model expressing the rate of smoke production at 400 kW in the room corner test (ISO 9705), based on data from the cone calorimeter (ISO 5660-1).

9.4 Experimental methods

9.4.1 Dual chamber test

This test method described in ISO/TR 5924 is designed to measure the smoke production of essentially flat materials/products whose surface is exposed to thermal irradiance of up to 50 kW/m^2. Horizontal orientation is used. Smoke is generated in one compartment of a box using a modified ignitability test apparatus (ISO 5657) without the pilot flame. The smoke is then accumulated in a second chamber (volume about 1,2 m^3) in which the smoke is stirred by a fan and the optical density measured by a horizontal white light beam. The maximum smoke density at five irradiance levels from 10 kW/m^2 to 50 kW/m^2 is determined.

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This test method is of static, cumulative type. The specimens are burned either by smouldering or flaming combustion depending on the product and irradiance level used.

9.4.2 Cone calorimeter

ISO 5660-1 currently specifies how the cone calorimeter is used to measure rate of heat release. However, ISO 5660-2 is being developed to measure smoke production. In this test method, smoke is produced in the normal cone calorimeter test conditions (horizontal orientation, irradiance usually between 25 kW/m^2 and 75 kW/m^2). The smoke is sucked into the exhaust duct where the light transmission (extinction coefficient) is measured by using a helium-neon laser. The extinction coefficient is measured as function of time. Further analysis makes use of the mass loss rate and volume flow rate measurements. The average specific extinction area ($\sigma_{m,\text{ave}}$) is defined as follows:

$$\sigma_{m,\text{ave}} = \sum_i \frac{V_i k_i \Delta t}{m_\text{i} - m_\text{f}} \qquad (19)$$

where

V_i is the volume flow rate in the exhaust duct;

k_i is the extinction coefficient (according to equation 15);

Δt is the sampling time interval;

m_i is the initial specimen mass;

m_f is the final specimen mass.

This method is of the dynamic type and it is essentially related to flaming combustion, except that for certain products quite an important part of smoke is produced before the specimen ignites. The produced parameters (extinction coefficient, mass-scaled extinction values, smoke production rates, total smoke production values) can be used in modelling real scale fires/tests. A round robin arranged by ISO/TC 92/SC 1/WG 4 gave the following results of repeatability r and reproducibility R for the average smoke extinction area ($\sigma_{m,\text{ave}}$):

$$r = 30 + 0{,}16\ \sigma_{m,\text{ave}} \qquad (20)$$

$$R = 50 + 0{,}41\ \sigma_{m,\text{ave}} \qquad (21)$$

The multiplying factors 0,16 and 0,41 are dominating the results except for very low absolute values of smoke. In other words, the results mean that the repeatability value is slightly more than 16 % of the mean value of the parameter and the reproducibility value is slightly more than 41 % of the mean. Expressing these values as standard deviations the data show 6 % of mean value for repeatability and 15 % of mean value for reproducibility.

9.4.3 Room corner test

In the large-scale ISO room corner test described in ISO 9705, smoke is measured in the exhaust duct in a flow-through system, with white light and without mass loss determination of the burning products. The measurement principles are the same as in the cone calorimeter. Smoke production rates and total smoke production values are produced as results (annex B).

This method is of dynamic type. Available round robin values for rate of smoke production indicate the standard deviation of results made in different laboratories to be usually less than 10 %.

9.5 Conclusions on smoke production and obscuration

The theory to describe the optical properties of smoke including light attenuation is quite simple, even if there has been considerable confusion in the definition of symbols and units. The application of theory to test procedures is

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also clear, but predictive methods for large-scale performance on the basis of small-scale data are in the developing stage.

Among small-scale procedures, the dynamic cone calorimeter is most promising, even through its capability for smoke prediction on a large scale has not yet been fully proven. The advantages are several, for example high irradiance levels, mass-related smoke properties, known volume flow rate conditions, both rates and integrated data available, fewer restrictions in specimen thickness or orientation, and the possibility of simultaneous and independent determination of other fire parameters.

So far, research activities on bench and large-scale smoke test results for linings and surface products have shown that the large-scale smoke production cannot be accurately predicted by the use of bench-scale smoke test results alone. In large-scale tests, the area of burning material and the ventilation influence the subsequent flame spread, heat release rate and CO_2/CO ratio. Hence, when considering the relevance of bench-scale smoke opacity data, it is necessary to combine all the test data on these parameters as the basis for a more accurate prediction of large-scale smoke production. Such a combination seems to be a good basis for prediction of large-scale smoke production.

Studies also indicate that large-scale smoke production may be related to the time to flashover for the material. Correlations and models will be different, dependent on the time to flashover when tested according to ISO 9705. Finally, correlations and models predicting large-scale smoke production will refer to the pre-flashover phase of the fire development.

10 Modelling room fire growth — lining materials

10.1 General

The purpose of this clause is to give a short review of the models which describe fire growth on combustible lining materials and to define a limited number of scenarios which are of interest. Rapid fire growth on lining materials is most commonly due to upward flame spread and annex C describes this in some detail.

It should be noted that some of the models mentioned are still under development and therefore the information in annex C may not be quite up to date.

10.2 Selecting scenarios

10.2.1 General

Full-scale scenarios which have to be investigated include:

a) small room scenario;

b) large room scenario;

c) room-corridor scenario.

This list gives only the outline or frame for a scenario specification. Factors that have to be specified include geometry and location of burner or ignition source, burner programme or heat output from ignition source, size and geometry of room and openings, application of the lining material to walls and/or ceiling, etc. The burner or ignition source is assumed to be adjacent to or in contact with the lining material.

10.2.2 Small room scenario

A good description of the conceptual formulation of wall fire spread in a room is given in [41]. It is evident from this description that a solution of the wall fire growth phenomena on a fundamental basis requires a modelling structure involving a number of heat transfer, fluid dynamics and combustion phenomena. In order to use analytical or numerical calculation methods, a number of simplifications will have to be introduced.

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Two approaches have been used. In the first, flame spread is modelled independently of the room fire process and no account is taken of radiative feedback from the upper gas layer or other environmental factors. The models are linked to a specified scenario, the room corner test as defined by NT FIRE 025 (ISO 9705), but they vary greatly in their degree of sophistication. The models described in [42], [43] and [44] are to a considerable extent based on experiments with a number of parameters determined empirically, in some cases by the use of regression analysis or other statistical methods. The results from the cone calorimeter are input to the models.

An example of an advanced model with respect to using available fire physics is described in [23]. Using flame length correlations and equation (C.1) in annex C, flame spread velocity and heat release rate are calculated. Results from the cone calorimeter are used as input data. This model can potentially be used on geometries and strength of ignition source that differ somewhat from those in ISO 9705.

The second approach consists of models which do take account of the room fire process. The model described in [24] simulates fire growth on wall and ceiling materials subjected to the ISO 9705 room corner test. The model described in [23] treats the case of an ISO 9705 room, and a 1/3 scale of it, with combustible linings mounted on walls only. Concurrent flame spread and downward flame spread are taken into account in both models. Input is from the cone calorimeter. LIFT apparatus results can be used additionally for somewhat better results.

The models described in [31] and [35] are purely flame spread models, and use theories considerably more sophisticated than those described in clause C.2 of annex C. Efforts are now under way to link these flame spread models to two-zone models to get information on pre-heating of the material and other environmental factors. An example is the model described in [33] which is now being linked to the well known two-zone model FAST [45]. The results from both standard and non-standard bench-scale tests are input to the flame spread models.

10.2.3 Room-corridor spread

Both experimental and modelling work with regards to fire growth on combustible linings in a room-corridor scenario is scarce. However, experimental and theoretical work on fire growth on floor coverings has been carried out and is described in detail in [33] and [36].

10.3 Factors affecting vertical upward flame spread

Clause 7 gives a short discussion on flame spread. Moreover references [27], [30], [34], [35], [37] and [38] describe, with varying degree of sophistication, theories and models for vertical upward flame spread on large surfaces. Annex C reviews the theory presented in [39], which is a thermal theory for upward flame spread on thick solids and leads to an integral equation of the Volterra type for the velocity of spread. The equation was solved analytically for several cases [40] and some of the practical results are given in annex C.

The solutions show that the parameters which determine whether flame spread on a material will accelerate or decelerate are time to ignition t_{ig} and material heat release rate characteristics, i.e. average heat release rate $\dot{Q}''_{ave}$ or the peak heat release rate $\dot{Q}''_{max}$ and the decay coefficient λ. These material parameters can all be determined in the cone calorimeter. An additional parameter flame length coefficient K varies with the scenario considered (flame spread up a wall, in a corner, under a ceiling, in a ceiling/wall intersection, etc.).

10.4 Possible relationships between limit states and classification

The models described in the previous clauses are probably too complex to be used directly by the regulator in order to classify or rank lining materials. A methodology is outlined in [23] where the limit state, for example, time to flashover, is expressed as an analytical function of design parameters (results from bench-scale tests). Such an expression has several advantages for a classification or a ranking order system:

a) using the analytical expression instead of running the complete simulation model will not significantly increase variability or uncertainty;

b) relevant flammability parameters measured in the bench-scale tests can be identified and ranked according to their importance;

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c) the influence of uncertainty and variability in bench-scale test results on the overall reliability of the classification procedure can be estimated;

d) the influence of computer modelling uncertainty on classification reliability can be estimated and different models compared.

As an example, the model described in [23] was used to calculate several hundred values of time to flashover as a function of a wide range of fictitious bench-scale test results. Time to flashover was expressed in terms of the following bench-scale test parameters

$$t_{f0} = a_0 (k\rho c)^{b_1} \phi^{b_2} T_{ig}^{b_3} (\dot{Q}''_{max})^{b_4} \lambda^{b_5} \qquad (22)$$

By using linear regression analysis, the pre-exponential and the exponential constants in the above equation were determined, resulting in an equation with a coefficient of determination, R^2, of 0,98. A similar expression was obtained to calculate the maximum rate of heat release in room fires when flashover does not occur.

Reference [23] discusses, as an example, the importance of the flame spread parameter, ϕ (from the LIFT apparatus). Excluding this parameter from the regression equation results in a measurable and marked increase in variability or uncertainty.

Heat released in the early stages of the fire is generally more hazardous than heat liberated later. The exponentials in the regression equation indicate how the heat release should be weighted with time. As a result, the whole heat release curve resulting from the cone calorimeter test can be expressed in a single parameter I_Q, the integrated, time weighted heat release index [40]. Introducing a second index I_{ig} (= $1/t_{ig}$), similar regression equations as those described above can be derived.

In summary, great progress has been made with respect to modelling fire growth on lining materials. If scenarios of interest can be defined then the models can be replaced by simple analytical expressions through the use of statistical methods, leading the way towards a reliability-based classification procedure.

It should be noted, however, that certain environmental factors have not been taken into account. Oxygen concentration, for example, can be taken into account in the models but is not considered in the bench-scale tests. The issues of classification of reaction to fire performance are discussed in more detail in ISO/TR 11696-2.

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Annex A

How to use piloted ignition test data — A rational approach

The time to piloted ignition is measured for thick slabs of a cellulosic flooring material in a bench-scale test over a range of irradiance levels. The results are given in Table A.1.

Table A.1 — Ignition data for a cellulosic flooring material (ISO 5660)

$\dot{q}''_{e}$ kW·m^{-2}	t_{ig} s
20	587
24	242
29	173
32	97
38	55
42	41
46	34

The emissivity of the material is approximately 0,9, and the convective heat transfer coefficient that characterizes the ignition test apparatus is estimated at 15 W·m^{-2}·K^{-1}. Figure A.1 shows a graph of $(1/t_{ig})^{0,55}$ plotted as a function of $\dot{q}''_{e}$. The intercept with the abscissa of a straight-line fit in this figure indicates that the critical heat flux for ignition, $\dot{q}''_{cr}$ is equal to 13,9 kW·m^{-2}. Solution of equation (2) in clause 6, with ε = 0,9 and h_c = 15 kW·m^{-2}·K^{-1}, gives T_{ig} = 354 °C and h_{ig} = 37,5 kW·m^{-2}·K^{-1}. Finally, the slope of the line, based on equation (1) in clause 6, leads to $k\rho c$ = 0,383 kJ^{2}·m^{-4}·K^{-2}·s.

The same flooring material is exposed in a room fire test. The measured irradiance to the floor can be approximated by the linear curve shown in Figure A2. The convection coefficient for the floor is estimated at 12 kW·m^{-2}·K^{-1}, and the temperature of the air in contact with the floor is equal to ambient, T_{∞} = 20 °C. Furthermore, it is assumed that the flooring material is sufficiently thick to behave as a semi-infinite solid. When does the material ignite if a small pilot flame is present near the floor?

For a semi-infinite solid exposed to a heat flux that varies with time, surface temperature as a function of time can be calculated with Duhamel's integral

$$T_s(t) - T_{\infty} = \frac{1}{\sqrt{\pi k\rho c}} \int_0^t \frac{\dot{q}''_{net}(\tau)}{\sqrt{t-\tau}} d\tau \quad \text{(A.1)}$$

with the net heat flux to surface given by

$$\dot{q}''_{net}(\tau) = \varepsilon \dot{q}''_{e}(\tau) - h_c\left[T_s(\tau) - T_{\infty}\right] - \sigma\varepsilon\left\{\left[T_s(\tau) + 274\right]^4 - (T_{\infty} + 273)^4\right\} \quad \text{(A.2)}$$

Equation (A.1) can be solved numerically. The calculated time to piloted ignition is the time when $T_s = T_{ig}$. For the exposure conditions described above, the calculated ignition time is 265 s. This is shortly after flashover, which occurred in the room fire test at 248 s.

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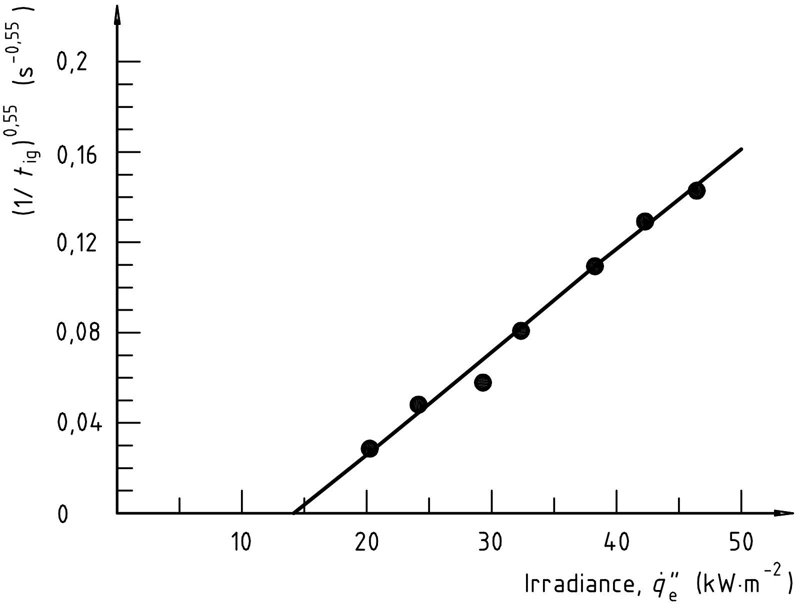

Figure A.1 — Correlation of ignition data for a cellulosic flooring material

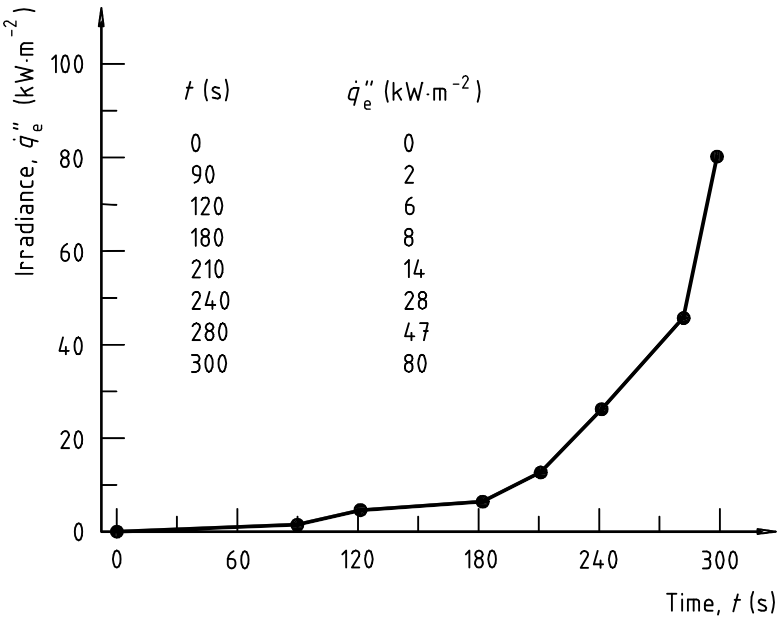

Figure A.2 — Irradiance to the floor measured during a room fire test

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Annex B

How to use test results of smoke production — A rational approach

The rate of smoke production in the room corner (ISO 9705) type of test is a measure of the amount of visible smoke flowing out of the room. The related hazard situation is one in which the smoke is accumulated in a space outside of the test room. Critical conditions occur when people in the reference space are not able to escape due to the loss of visibility. It would be logical to connect critical conditions and criteria on smoke production to the hazard scenario.

B.1 Critical smoke densities

T. Jin has carried out a considerable amount of research on the effect of loss of visibility on human behaviour [1], [2]. One of the findings was that one of the limiting smoke density (extinction coefficient) for effective escape is:

a) for people unfamiliar with the escape route: 0,15 m^{-1} or 0,65 dB/m (visibility of 15 m)

b) for people familiar with the escape route: 0,50 m^{-1} or 2,2 dB/m (visibility of 4,5 m).

Possible criteria for rate of smoke production could be based on the critical values above, because they represent best available knowledge on human response to smoke. The following procedure could be used.

B.2 Total smoke production

B.2.1 Spaces for people unfamiliar with the escape route

NOTE All values in brackets are only meant to give an arbitrary calculation example.

a) Assume that there is a reference volume V_s = 500 m^3.

b) Assume that a fraction f = 0,9 of the inflowing smoke will be exhausted out of the reference space.

c) Calculate the smoke density (extinction coefficient) k in the reference space by the following equation:

$$k=\int_0^t \frac{(1-f)\dot{S}}{v_s}\mathrm{d}t \qquad \text{(B.1)}$$

where t is test time, $\dot{S}$ is smoke production rate (m^2/s) and Δt_i is sampling interval.

d) Determine the time when k = 0,15 m^{-1}.

Limiting criteria

The critical smoke density of 0,15 m^{-1} shall not be reached within the test period.

For a 20 min test this criterion corresponds to an average rate of smoke production of 0,63 m^2/s.

B.2.2 Spaces for people familiar with the escape route

Repeat the calculations as before with the following change in assumptions:

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Determine the time when k = 0,50 m^{-1}.

The limiting smoke density of 0,50 m^{-1} shall not be reached within the test period.

In a 20 min test this criterion corresponds to an average rate of smoke production of 2,1 m^2/s.

B.3 Calculation of smoke production over a standard (1 min) period

B.3.1 Spaces for people unfamiliar with escape route

This example is calculated for cumulative smoke production over 1 min.

a) Assume that there is a reference volume V_s = 500 m^3.

b) Assume that a fraction f = 0,50 of the inflowing smoke will be exhausted out of the reference space.

c) Calculate the accumulated smoke density (extinction coefficient) in the reference space for any period of 60 s by the following equation:

$$k(t) = \int_t^{t+60} \frac{(1-f)\dot{S}}{v_s} \mathrm{d}t \qquad \text{(B.2)}$$

NOTE The calculation may be done also by using a 60 s floating average of rate of smoke production.

The limiting smoke density 0,15 m^{-1} shall not be reached during any period of 60 s of the test.

B.3.2 Spaces for people familiar with the escape route

The limiting smoke density 0,50 m^{-1} shall not be reached during any period of 60 s of the test.

This criterion corresponds to maximum average rates of smoke production over a 60 s period of 2,5 m^2/s in spaces for people unfamiliar with the escape route and 8,3 m^2/s in spaces for people familiar with the escape route.

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Annex C

Mathematical modelling of upward flame spread and HRR in full scale

C.1 Background

Many of the models mentioned in clause 10 mainly examine theories of upward flame spread and how heat release rate can be calculated in the room corner test. Here, upward flame spread theories will be examined to show how they can be used to assess how hazardous the material will be in a given end-use situation (in a corner, on a wall, under a ceiling, etc.).

Modelling flame spread over a material surface, and the subsequent heat release rate from the material, will be divided into two cases: simple analytical modelling and numerical simulation. Both methods are based on the assumption that the cone calorimeter is used as a basis to determine the heat release rate from the material.

C.2 Analytical methods

C.2.1 General

Analytical methods to determine the fire growth characteristics of a material demand that many simplifying assumptions are made. At this stage, the thermal feedback from the compartment in which the material is found will not be taken into account. The purpose of this section is thus to outline a few possible methods to assess a rough flame spread propensity of a material. Observe that the following is just a first step on how to approach the problem.

Assuming that the primary interest is in assessing the fire growth characteristics of a material, the most hazardous condition is assumed to occur when the material spreads flame upwards.

The following steps will be necessary:

a) Represent the cone calorimeter data mathematically. Two very simple approaches will be outlined below.

b) Set up the concurrent flow flame spread equation given in the original modelling chapter.

Solve the upward flame spread equation for each of the mathematical representations from step a). Also solve these for the different concurrent flow flame spread scenarios (flame spread up a flat wall originated by a line burner, flame spread up a corner originated by a burner, and flame spread under a ceiling, originated by a certain flame area in the ceiling).

C.2.2 Mathematical representation of the cone calorimeter data

Two very simple methods are outlined here; several other methods exist. The first method is described in the original modelling chapter, i. e. $\dot{Q}''(\mathrm{t}) = \dot{Q}''_{\mathrm{max}}\mathrm{e}^{-\lambda t}$ where $\dot{Q}''_{\mathrm{max}}$ is the peak heat release rate and λ is a decay coefficient (see Figure C.1, taken from Karlsson [3]). This representation is not valid for all types of materials.

Another simple method is to evaluate a certain $\dot{Q}''_{\mathrm{ave}}$ and a t_{bo} where $\dot{Q}''_{\mathrm{ave}}$ is an average heat release rate over the period from ignition until time to burn-out, t_{bo} (see Figure C.2).

Both mathematical representations leave much to be desired but may in many cases prove a very simple tool to evaluate the flame spread propensity of a material. The two representations are chosen here only to exemplify the potential of the whole methodology.

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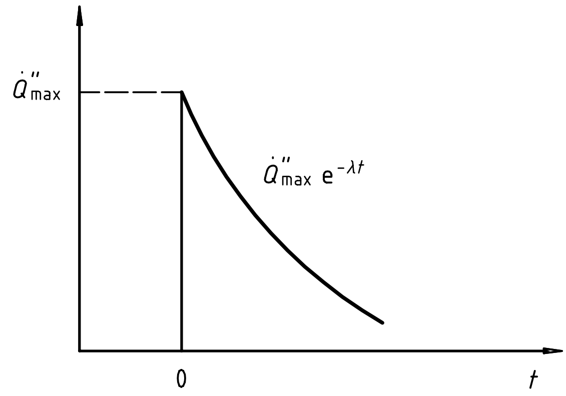
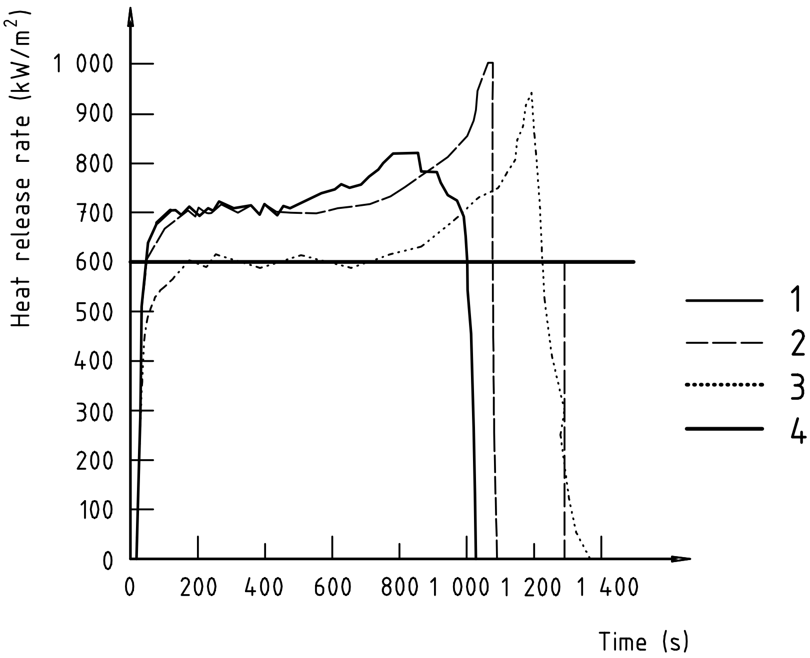


Table C.1 — Representing HRR by exponential decay



Key

1 Foil only

2 Steel frame

3 Insulated frame

4 $\dot{Q}''_{ave}$

Figure C.2 — Heat release rate (HRR) of PMMA represented by an average value (taken from reference [4])

C.2.3 Setting up the equation for the concurrent flow flame spread

The equations will be set up in a similar way as was done in [5]. This can be done in many different ways depending on the scenario being treated. The basic assumption made is that the velocity can be written as

$$V(t) = \frac{x_f(t) - x_p(t)}{\tau} \tag{C.1}$$

where

x_p is the pyrolysis length;

x_f is the flame length;

$V(t)$ is the velocity of pyrolysis front;

τ is the time to ignition.

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In order to simplify the treatment we shall take no account of burn-out, meaning that the following equations are only valid while the flame from the gas burner and the flame from the burning material can be assumed to be one, continuous flame.

An example of a relatively general equation is given below. It is based on the assumption that the velocity can be written as

$$V(t)=\frac{1}{\tau}\left[K\left(\dot{Q}_b+x_{po}W\dot{Q}''(t)+\int_0^t W\dot{Q}''(t-t_p)V(t_p)\mathrm{d}t_p\right)^n-\left(x_{po}+\int_0^t V(t_p)\mathrm{d}t_p\right)\right] \quad (C.2)$$

The symbols are discussed in [3]. The first term in the brackets on the right hand side represents x_f, the flame height. This flame height is assumed to be due to heat release from three sources: the gas burner, the initially ignited material and the HRR due to the upward spread of flame. Note that here $\dot{Q}''(t)$ denotes results from the cone calorimeter. In the numerically based models one uses the results directly; for analytical solutions one must substitute the mathematical representation for $\dot{Q}''(t)$. We will here only use the two simple mathematical representations shown in Figures C.1 and C.2.

We are interested in setting up and solving the equation for 6 different cases according to Table C.1.

Table C.1 — Cases to be considered (preliminary)

Case	HRR representation	Scenario	Igniter
1	Exponential	Wall	Line burner
2	Exponential	Corner	Square burner
3	Exponential	Ceiling	Flame area, A_o
4	Average $\dot{Q}$	Wall	Line burner
5	Average $\dot{Q}$	Corner	Square burner
6	Average $\dot{Q}$	Ceiling	Flame area, A_o

As an example we shall show how the flame spread velocity equation is set up for Case 4:

$$V(t)=\frac{1}{\tau}\left\{K\left[\dot{Q}_b+x_{po}\dot{Q}''_{ave}W+\int_o^t w\dot{Q}''_{ave}V(t_p)\mathrm{d}t_p\right]-\left[x_{po}+\int_0^t V(t_p)\mathrm{d}t_p\right]\right\} \quad (C.3)$$

Here x_{po} is the initial pyrolyzing area, which is equal to the igniter flame height $K\dot{Q}_b$. For the line burner case the burner width W and the burner output $\dot{Q}_b$ must be specified. For the square burner the size and the burner output must be specified. For the ceiling case the initial flame area A_o under the ceiling must be specified. Here, K is the flame height coefficient. This constant changes for the wall, corner and ceiling cases. Also, either Q''_{ave} or Q''_{max} and λ must be specified. The equation can, however, be solved in terms of the above variables and analysed.

Thomas [5] discusses these solutions in greater detail and Karlsson [3] has earlier shown solutions to Cases 1 to 3. We shall now show, as an example, how Case 4 can be solved and used in practice.

C.2.4 Solutions for the velocity and heat release rate in Case 4

We shall represent the cone calorimeter results mathematically as shown in Figure 2, and set $\dot{Q}''(t) = Q''_{ave}$. Consequently, the following equations are only valid for a time t_{bo} (time to burn-out). Note that Quintiere [6] has given solutions where account has been taken of the burn-out time. Equation (C.3) reduces (by applying Laplace transforms) to

$$V(t)=\frac{K\dot{Q}_b}{\tau}A\mathrm{e}^{(A-1)t/\tau} \quad (C.4)$$

where $A = K\dot{Q}''_{ave}W$.

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We can see that if $A > 1$ the flame spread will propagate exponentially, for $A < 1$ the spread will decelerate and for $A = 1$ the flames will spread upwards at a constant rate. The numerical value of the velocity will depend on the ignition time τ, the burner output $\dot{Q}_b$, the flame height constant K and the width of the material strip burning (assumed to be as wide as the line burner). In this case (flame heights against a wall) K is preliminarily taken to be 0,01 m/kW (further examination of data is necessary).

Example: Assume we have a 400 mm wide, 3 m high PMMA slab, ignited at floor level by an equally wide burner with an output of 30 kW. Assume this is the same material as was tested in the cone calorimeter with the results shown in Figure C.2. What will the upward flame spread velocity be? And what will the heat release rate be?

Answer: Time to ignition can be calculated as a function of $k\rho c$, ignition temperature and the incident heat flux. Alternatively the ignition results can be taken directly from the cone calorimeter data for an incident heat flux representative for the case to be considered. We will here assume the incident heat flux to have an average value over the flame height of 30 kW/m^2, a rough estimate of the time to ignition in this case is $\tau \approx 100$ s. $\dot{Q}''_{ave}$ taken from Figure C.2 to be 600 kW/m^2. This gives the equation for the velocity as

$$V(t) = 0{,}072\ \mathrm{e}^{0{,}014t} \qquad \text{(C.5)}$$

The result for the velocity is given in Figure C.3.

We are now interested in knowing the pyrolysis length as a function of time. This is written as

$$x_p(t) = x_{po} + \int_0^t V(t_p)\,\mathrm{d}t_p \qquad \text{(C.6)}$$

which is solved as (knowing that $x_{po} = K\,\dot{Q}_b$)

$$x_p(t) = K\,\dot{Q}_b + \frac{K\dot{Q}_b A}{(A-1)}\left[\mathrm{e}^{(A-1)t/\tau} - 1\right] \qquad \text{(C.7)}$$

where, as before, $A = 2{,}4$, $\dot{Q}_b = 30$ kW, $K = 0{,}01$ m/kW and $\tau = 100$ s. The results are shown in Figure C.4.

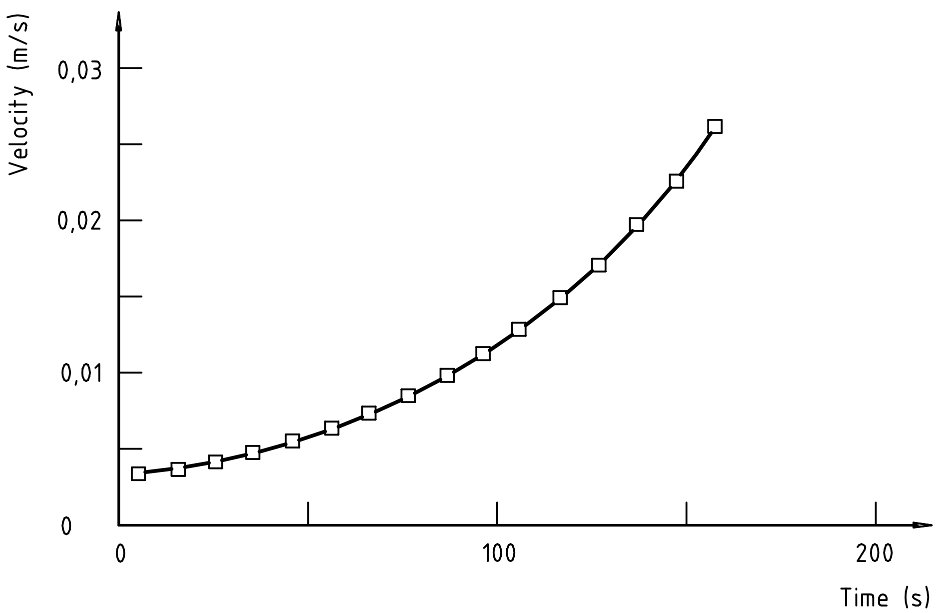

Figure C.3 — Velocity of the pyrolysis front

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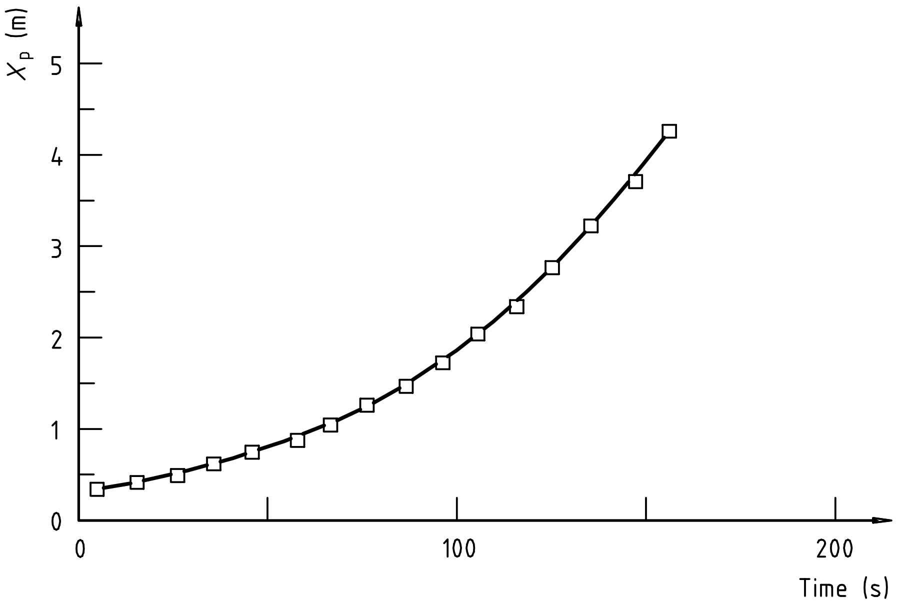


Figure C.4 — Position of the pyrolysis front

Figure C.4 shows that at time $t \approx 140$ s, the pyrolysis front has reached the top of the 3 m high PMMA slab. Observe that the burner first heats the bottom part of the slab for 100 s before ignition and flame spread.

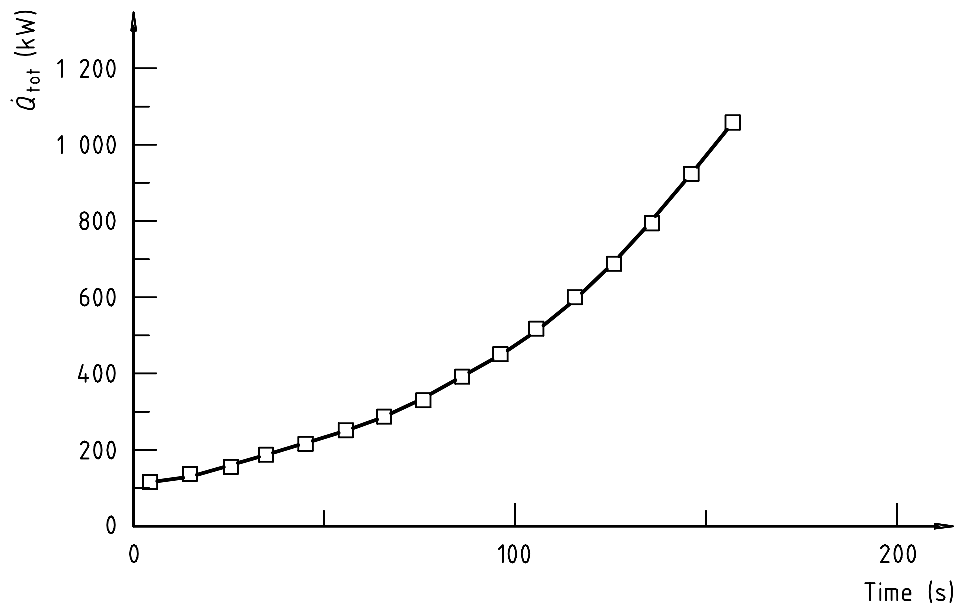
The heat release rate in this case can be written as:

$$\dot{Q}(t) = \dot{Q}_b + x_{po}\dot{Q}''_{ave} W + \int_0^t \dot{Q}''_{ave} W V(t_p)\,dt_p \quad \text{(C.8)}$$

which results in:

$$\dot{Q}(t) = \dot{Q}_b + x_{po}\,\dot{Q}''_{ave} W + \frac{K \dot{Q}_b A}{(A-1)}\left[e^{(A-1)t/\tau} - 1\right]\dot{Q}''_{ave} W \quad \text{(C.9)}$$

The results for this example are shown in Figure C.5.



At time $t \approx 140$ s the heat release is close to 1 MW.

Figure C.5 — Heat release rate for the PMMA slab

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C.3 Numerical methods

Using numerical methods to solve equation (C.2) has several advantages, but also some disadvantages. The advantages are mainly the following:

a) Material heat release rate can be taken directly from the cone calorimeter, no mathematical representation, such as in Figures C.1 and C.2, is necessary.

b) Flame height can be expressed as a non-linear function of heat release rate. Thus the exponent n in equation (C.2) can be set to, for example 2/3, which in some cases may be more realistic than assuming a linear dependence on heat release rate.

c) Pre-heating of the material by the gas layer can be taken into account as well as varying heat flux over the flame height. This means that the influence of the geometry of the compartment can be taken into account. In this case the thermal inertia, $k\rho c$, must be known and time to ignition must be calculated using equation (1b) in [1].

d) Burn-out of the material can be taken into account.

The disadvantages of a numerical solution are that the physical meaning of the terms in equation (C.2) gets somewhat clouded and the behaviour of the solution can not be directly analysed.

Also, a numerical solution requires that a computer program be written, with an input section, calculation section and an output section. A few computer programs exist where equations such as equation (C.2) are solved. Examples of such programs were given in clause 10 but these are specialized programs for certain scenarios (room corner test).

C.4 Simple method for assessing material flame spread propensity

C.4.1 General

If a rough estimate of the flame spread propensity of a material in a certain end use condition is needed, the following methodology can be used, (see Figure C.6):

a) Do a mathematical representation of the cone calorimeter HRR curve, depending on the shape of the curve (a value for $\dot{Q}''_{ave}$ or $\dot{Q}''_{max}$ and λ).

b) Assume a value for K, the flame height constant from the Table C.2 (preliminary).

Table C.2

Scenario	Value of K
Flame spread up a wall	0,01
Flame spread in a corner	0,015
Flame spread under a ceiling	0,02

c) Estimate the flame spread propensity of the material.

If using $\dot{Q}''_{ave}$ then calculate $A = K\, \dot{Q}''_{ave}\, W$ where W is the width of the burner igniter. If $A > 1$ the flame spread will propagate exponentially, for $A < 1$ the spread will decelerate.

If using $\dot{Q}''_{max}$ and λ then check if $\lambda\tau = (1–A)^2$ where $A = K\, \dot{Q}''_{max}\, W$. If this is the case then the flame spread will accelerate. Here one must have information on τ, the time to ignition. This must be estimate at the irradiant heat flux in the end use condition. For a thin flame from a line burner, the heat flux can be assumed to be 20 kW/m^2 to

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30 kW/m^2. From a corner burner with a relatively thick flame the heat flux can be assumed to be 40 kW/m^2, typical for the room corner test burner at 100 kW energy output.

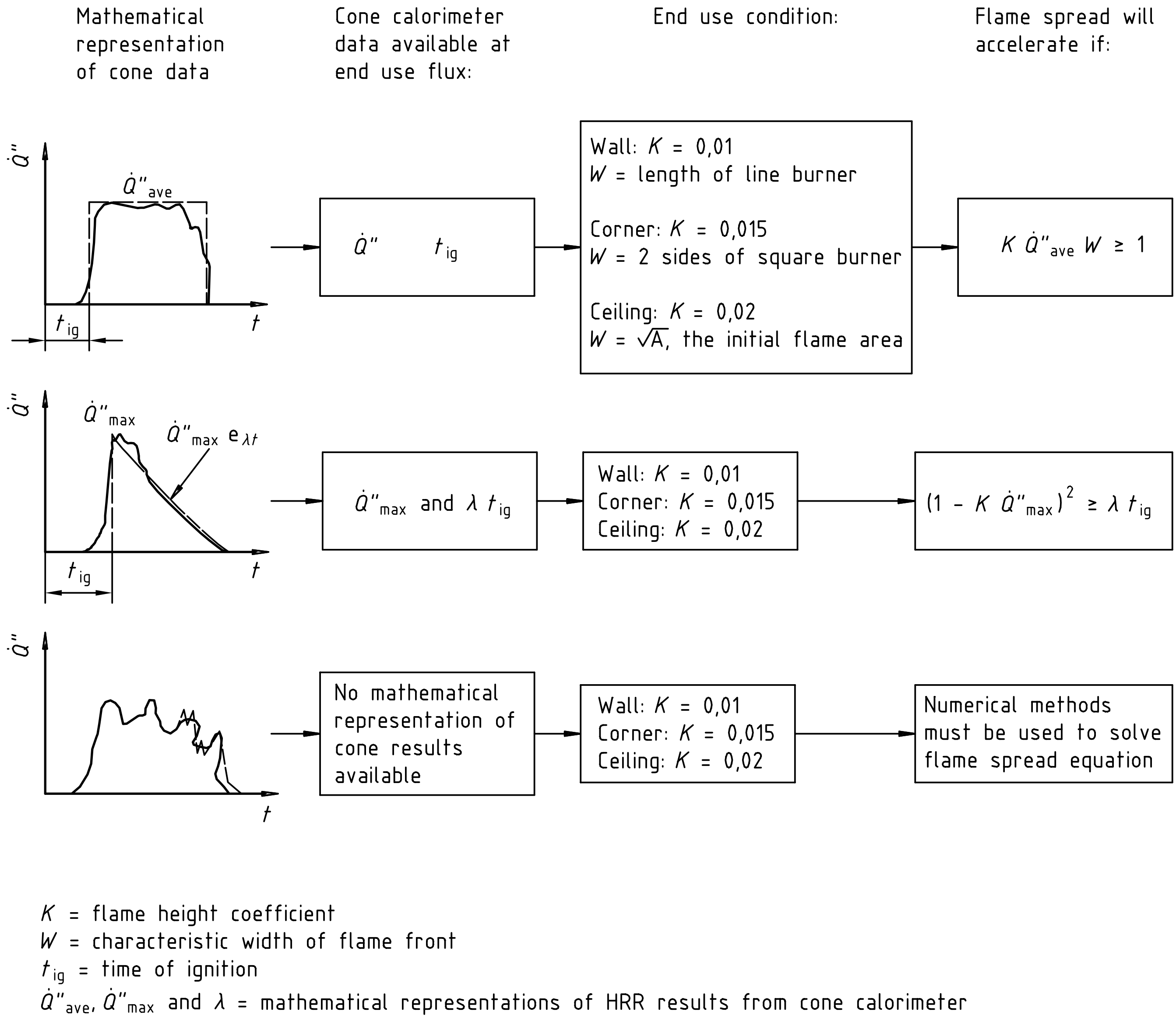

Figure C.6 — Methodology estimating flame spread propensity of a material

C.4.2 Calculated examples

Will a material exhibit accelerated flame spread in a certain end use condition?

Assume that a slab of material is ignited at floor level by a line burner of width 40 cm.

e) Assume this is the same material as was tested in the cone calorimeter with the results shown in Figure C.2 ($\dot{Q}''_{ave}$ = 600 kW/m^2). Will the flame accelerate?

Flame spread up a wall $\Rightarrow K$ = 0,01 m/kW, W = 0,4 m

$K \times \dot{Q}''_{ave} \times W$ = 0,01 × 600 × 0,4 = 2,4 which is > 1, $\Rightarrow$ accelerating flame spread.

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f) Assume the material is particle board. HRR from the cone will be represented as a decaying process, i.e. with $\dot{Q}''_{max}$ and λ. Karlsson [3] has presented such values for particle board (at external heat flux 30 kW/m^2) as $\dot{Q}''_{max}$ = 200 kW/m^2 and λ = 0,003 s^{-1}. Time to ignition at this heat flux is approximately 90 s.

Flame spread up a wall ⇒ K = 0,01 m/kW

$(1 - K \times \dot{Q}''_{max})^2 \geqslant \lambda \times t_{ig}$?

$(1 - 0{,}01 \times 200)^2 \geqslant 0{,}003 \times 90$?, which gives $1 \geqslant 0{,}27$?

⇒ Yes, accelerated flame spread.

g) The particle board is ignited with a smaller burner from which the heat flux is only 20 kW/m^2. The HRR from the cone is very similar at 20 kW/m^2 and 30 kW/m^2 external flux. Time to ignition is, however, much longer at 20 kW/m^2, t_{ig} = 240 s. Will the flame spread accelerate?

as above:

$(1 - 0{,}01 \times 200)^2 \geqslant 0{,}003 \times 240$?, which is $1 \geqslant 0{,}72$?

⇒ Yes, the flame will also accelerate in this case.

h) Wood panel, spruce, is in the same end use condition as above. This has been tested in the cone calorimeter and the HRR curve can be mathematically represented as $\dot{Q}''_{max}$ = 170 kW/m^2 and λ = 0,0075 s^{-1}. At 30 kW/m^2 the ignition time is approximately 80 s.

as above:

$(1 - 0{,}01 \times 170)^2 \geqslant 0{,}007\,5 \times 80$?, which is $0{,}49 \geqslant 0{,}6$?

⇒ No, the flame will not accelerate in this case (but is very close to doing so).

i) The same material as above but it is mounted in a corner. Will the flame spread accelerate?

Flame spread in a corner ⇒ K = 0,015 m/kW

as above:

$(1 - 0{,}015 \times 170)^2 \geqslant 0{,}007\,5 \times 80$?, which is $2{,}4 \geqslant 0{,}6$?

⇒ Yes, the flame will accelerate in this case.

C.5 Flame front velocity and HRR in end use condition

If further information is needed, for example the heat release rate in the full scale scenario, then the following can be considered.

a) When results from the cone calorimeter can be represented by an average value ($\dot{Q}''_{ave}$) then

— flame spread velocity in end use condition can be calculated using equation (C.4)

— HRR in end use condition can be calculated using equation (C.9).

An example of these calculations is given in section C.2.3

b) When results from the cone calorimeter can be represented by a maximum value and a decaying parameter ($\dot{Q}''_{max}$ and λ) then

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— flame spread velocity in end use condition can be calculated using equations given by Karlsson [3]. These are, however, somewhat cumbersome and are not reproduced here

— HRR in end use condition can be calculated using equations given by Karlsson [3]. Again, these are somewhat cumbersome and are not reproduced here.

— When results from the cone calorimeter can be represented mathematically, equation (C.2) shall be solved numerically to give the velocity of the flame front. These results can be numerically integrated to give the HRR.

— The ideal situation is to use a computer program which reads the cone calorimeter curve directly and gives a numerical answer [as in case c)]. Such models exist but they treat only a certain scenario (room corner test).

C.6 Final remarks

This annex shows ways of using data from the cone calorimeter to estimate flame spread propensity of materials in various end use conditions. Heat release rate in the end use condition can also be calculated. The methods used are fairly rough, recently developed and the numbers quoted here should be seen as being preliminary since they have not been compared with experimental values.

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