Proposal of CFPA Europe European Guideline

Fire safety engineering concerning

Fire resistance of buildings

- Draft version Guidelines Commission -
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1 Introduction

The fire resistance of buildings is the key objective in fire protection processes for human life, the buildings and their contents. The Interpretative Document No. 2 of the 89/106/EC Directive provides that the stability of the main structure of a construction work in case of fire, if necessary:

- to provide for the safety of the occupants during the time they are assumed to remain in the building,
- to increase the safety of rescue teams and fire-fighters,
- to guard against the collapse of a building, causing injury to people,
- to allow the production constructs involved in fire safety to carry out their functions for the necessary time.

The stability performance of a building has to be ensured through sufficient fire resistance of the main structure. This objective can be reached with the following two steps:
1. establishing the fire resistance performance that the structure should ensure,
2. designing and/or verifying the real structure to determine if the required performance is actually achieved.

1.1 Establishing the fire resistance performance

The fire resistance performance correspond to the period of time for which it is required that the structure maintains its load-bearing capacity (and any other required safety characteristic).

This required period depends on the goals of national regulators. The following are examples of the goals provided from some regulators:
- no specified fire resistance requirements for buildings with limited fire load density or where the consequences of collapse of structures are acceptable,
- fire resistance for a specified but limited period of time, where the time requirements can be specified to allow for safe evacuation of occupants and intervention of rescue teams,
- fire resistance of the structure to ensure that it can survive a full burn out of all combustible materials in the building, or a specific part of it, without taking into account the intervention of fire brigades or rescue teams.

The required fire resistance performance is basically related to specific considerations:
- on the building use
- on the fire load density.

In the first case the references are related to national prescriptive standards that can determine specific fire resistance values for some particular activities (i.e. schools, hotels, hospitals, theatres, etc.)

For example in the UK the requirements of fire resistance of buildings are listed in the Building Regulations for England and Wales, with regional differences that can be extracted from specific documents for construction in Scotland and Ireland.

In Italy, however, the requirements of fire resistance are determined by the fire prevention regulations issued by the Ministry of the Interior or by the Ministerial Decree January 14, 2008: Approval of new technical standards for construction.

In the latter case the fire load density can be calculated according to Annex E of EN 1991-1-2 (Eurocode 1: Action on Structures – Part 1-2: General actions – Actions on structures exposed to fire).

Annex E presents a method for calculating design fire load densities based on characteristic values from survey data for different occupancies. The characteristic values are modified according to the risk of fire
initiation and the consequence of failure related to occupancy and compartment floor area. Active fire safety measures are taken into account through a reduction in the design fire load density. This approach is not accepted in the UK NA, while in Italy this is the main method to define the fire resistance performance in buildings that do not fall within the scope of the national prescriptive standards.

1.2 Design and/or verification of fire resistance performance

Once established the required fire resistance it is possible to design the structure, or to verify that the existing structures meet the requirements. For the evaluation of fire resistance of structures the following possibilities are prevailing in EU member States:
- consideration of conventional fire scenarios
- consideration of natural fire scenarios.

Both methods are based on the following steps:
1. selection of the relevant design fire scenarios and determination of the corresponding design fires
2. determination of the reference temperature-time curve
3. calculation of temperature evolution within the structural members and calculation of the mechanical behaviour of the structure exposed to fire

EN1991-1-2 is principally concerned with the first two steps, while “Fire” parts of the other structural Eurocodes cover the last step.

1.2.1 Selection of the relevant design fire scenario and design fires

The choice of the design fire scenario will determine also the choice of the associated design fire to be used in subsequent: this choice should be determined on the basis of a fire risk assessment. In some cases the choice of fire scenario is implicitly connected with the reference temperature-time curve (see the following sections). For example the standard temperature-time curve (ISO 834) assumes that the whole compartment is involved in a fully developed fire at the same time and the same temperature applies throughout.

In other cases the choice is determined by further considerations: for example the Annex C of the EN 1991-1-2 (Eurocode 1: Action on Structures – Part 1-2: General actions – Actions on structures exposed to fire) examines a localized fire scenario, in which the fire develops only in a limited portion of the compartment.

1.2.2 Determination of the reference temperature-time curve

The international literature and technical standards (e.g. EN 1991-1-2) define two main groups of temperature-time curves:
- nominal (conventional) time-temperature curves (see 1.2.2.1),
- natural time-temperature curves (see 1.2.2.2)

There is also a simplified method to transform a natural fire curve in the corresponding standard ISO 834 fire curve: the equivalent time of fire exposure (see 1.2.2.3)

1.2.2.1 Nominal curves

Nominal curves are conventional and representative curves, usually expressed through a mathematical formula, which have no direct relationship to the characteristics of the building considered (e.g. fire load, thermal properties of compartment linings, ventilation condition, etc.).

The main nominal temperature-time curves are the following:
- standard temperature-time curve (see ISO 834 – Part 1)

\[ \theta_g = 20 + \log_{10} 345(8t+1) \]

- harmonized hydrocarbon fire curve,

\[ \theta_g = 1080(1 - 0.325 e^{-0.167t} - 0.675 e^{-2.5t}) + 20 \]

- external fire curve.

\[ \Theta_g = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + 20 \]

Temperature constant after 22 mins at 660°C
1.2.2.2 Natural curves
The method of determining the natural fire curves, with particular reference to computational fluid dynamics models, is discussed in deeper details in the following sections. This section provides only a general overview.

Natural temperature-time curves are usually obtained with calculation techniques based on considerations about the physical parameters of a particular building. These curves are always derived from the development of natural fire scenarios. Typically they should consider: the fire load (type, amount and burning rate), the air supply to fire, the geometry and size of enclosures (defined by the fire compartment), the thermal properties of materials, etc.

Depending on the particular fire safety strategy or engineering approach, further considerations can also include the influence of fire suppression installation (e.g. sprinkler installation), the fire brigade/rescue teams action (which may be initiated by fire detection installation) and so on.

The natural fire curve can be defined using a variety of fire models: each of these models has a specific field of application to take into account. The international literature and technical standards (e.g. EN 1991-1-2) define two major model categories:
- simplified models
- advanced models

Some examples of SIMPLIFIED MODELS include:
- **Parametric temperature-time curves** (e.g. annex A of the EN 1991-1-2)
  The model is valid for fire compartments up to 500 m² of floor area, without openings in the roof and for a maximum compartment height of 4 m. It is assumed that the fire load of the compartment is completely burnt out and that the fire load itself is not less than 50 MJ/m² and not more than 1000 MJ/m². Some of the factors taken into account are: the total area of enclosure (walls, ceiling and floor, including openings), the total area of vertical openings on all walls, the fire load, the thickness and characteristics of wall materials (density, specific heat, thermal conductivity), etc.
  The following image compares qualitatively the trend of parametric and standard ISO 834 fire curves.
- **Localised fires curves** (e.g. annex C of the EN 1991-1-2)
  The model is valid when the distribution of the fire load is limited to a portion of the compartment area: in many cases flashover is unlikely to occur.
  It considers the following parameters: the diameter of the fire, the rate of heat release, the convective part of the rate of heat release, the flame height along its axis, the distance between the fire source and the ceiling.

![Diagram of EN 1991 Parametric and Standard fire curve](image)

Appendix C of EN 1991-1-2 - Figure C.1

The **ADVANCED MODELS** should take into account the following:
- gas properties;
- mass exchange;
- energy exchange.
Available calculation methods usually include iterative procedures which require the use of specific software. One of the following models should be used:

- **one-zone models**: they assume a uniform, time dependent temperature distribution in the compartment;
- **two-zone models**: they assume an upper layer with time dependent thickness and with time dependent uniform temperature, as well as a lower layer with a time dependent uniform and lower temperature;
- **computational fluid dynamic (CFD) models**: they give the temperature evolution in the compartment in a completely time dependent and space dependent manner.

With these models must be considered at least the following factors: the volume of the enclosures, the fire load and ventilation conditions. Additional factors are: activation protection systems like smoke evacuation system, automatic sprinklers system, etc.

### 1.2.2.3 Equivalent time of fire exposure

It’s a simplified procedure explained in Appendix F of EN 1991-1-2: Eurocode 1: Action on Structures – Part 1-2: General actions – Actions on structures exposed to fire

It provides a quick and easy method of relating a real fire exposure to an equivalent period in a furnace with a standard fire curve (ISO 834). It’s mainly based on work on protected steel specimens, and recent analysis extended the use of the concept to unprotected steel for low fire resistance periods.

The use of this method is subject to approval by the national regulators: in UK is permitted, while in Italy is not allowed.

### 1.2.3 Calculation of temperature evolution within the structural members and calculation of the mechanical behaviour of the structure exposed to fire

Once defined the required performance level and the reference temperature-time curve, it’s possible to calculate the temperature evolution within the structural member and the mechanical behaviour of the structure to evaluate the overall fire resistance performance.

Both calculation involves the application of the Structural Eurocode (EC) Standards. They are a series of European standards that rule the design of structures. The following are the standards related to fire resistance aspects:

- **EN 1991-1-2** Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire

These standards provide alternative procedures to determine the fire resistance of a structural element:

- prescriptive, based on thermal actions given by nominal fires curves
- performance-based, which take into account thermal action given by natural fire curves
The following image illustrates these alternative procedures:

![Diagram](image1)

**Figure 1: alternative design procedures (source: EN 1991-1-2:2002)**

Both prescriptive and performance-based method follow the same basic steps:

- **calculation of the temperature distribution within the structure**: the following image illustrates an example for a steel structure. The Eurocodes Standards provide the necessary input data and formulas.
- **Determination of mechanical actions**: mechanical actions are responsible for the stress on the structures. They are of varied nature and differ basically for the duration of its application in relation to the average life of a work.

For fire design purposes the following actions have to be considered: permanent loads (e.g. weight of the structure itself), prestressing actions (for example), variable actions (snow, wind, etc.). indirect actions (e.g. impeded thermal expansion). The Eurocodes Standards provide data and formulas for calculating the mechanical actions which act in case of fire.

- **Mechanical analysis**: this step involves the application of calculations methods provided in the Eurocodes. In many cases, these calculations require the application of iterative procedures which require the use mechanical modelling software. The result of this last step is the fire resistance of the structure.

Verification of fire resistance should be:
- in the time domain: \( t_{fd} \geq t_{f,req} \)
- or in the strength domain: \( R_{fd,t} \geq E_{fd,t} \)
- or in the temperature domain: \( \Theta_d \leq \Theta_{cr,d} \)

where
- \( t_{fd} \) is the design value of the fire resistance
- \( t_{f,req} \) is the required fire resistance time
- \( R_{fd,t} \) is the design value of the resistance of the member in the fire situation at time \( t \)
- \( E_{fd,t} \) is the design value of the relevant effects of actions in the fire situation at time \( t \)
- \( \Theta_d \) is the design value of material temperature
- \( \Theta_{cr,d} \) is the design value of the critical material temperature

The calculation made using prescriptive procedures are usually easier, but conservative. The results are often summarized in “easy to read” tables which have, on the other hand, severe limits of application.


<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>El 30</td>
<td>60</td>
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<tr>
<td>El 60</td>
<td>80</td>
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<td>El 90</td>
<td>100</td>
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<tr>
<td>El 120</td>
<td>120</td>
</tr>
<tr>
<td>El 180</td>
<td>150</td>
</tr>
<tr>
<td>El 240</td>
<td>175</td>
</tr>
</tbody>
</table>

Limit of application: the ratio of clear height of wall to wall thickness should not exceed 40, to avoid excessive thermal deformation and subsequent failure of integrity between wall and slab.
The calculation made using performance criteria imply an analytical and more complex approach to the problem, but give a greater freedom in the structures design. As determined by Eurocodes, an analytical procedure for fire resistance shall take in account:
1. the potential heat exposure;
2. the beneficial effects of active and passive fire protection systems
3. the behaviour of the structural system at elevated temperatures;

2 Scope
As already mentioned in the introduction, this guideline proposal does not aim to provide methods for the calculation of the fire resistance of a structure, since these methods – as shown above – are already dealt with in the structural Eurocodes.

The purpose of this guide, instead, is to propose a methodological approach for the application of natural fire models, with particular reference to computational fluid dynamics models.

This approach allows to define the natural temperature-time curve, and thus the thermal stress to be applied subsequently to the models of structural calculation of fire resistance (fire exposure) of the Eurocodes.

3 Key terms

**Active fire protection measures**
Systems and equipment installed to reduce danger to persons and property by detecting fire, extinguishing fire, removing smoke and hot gases, or any combination of these functions.

**Design fire scenario**
A design fire scenario is a subsystem of fire scenarios and represents the most probable or onerous of them. They are a specific fire scenario on which an analysis will be conducted.

**Enclosure**
Space defined by boundary element (on all sides) around the point of the origin of the fire.

**Fire**
A process of a combustion characterised by emission of heat accompanied by smoke and / or flame.
Rapid combustion spreading uncontrolled in time and escape.

**Fire compartment**
An enclosed space in a building that is separated from other parts of the same building by enclosing construction having a specified period of fire resistance, within which a fire can be contained (or from which a fire can be excluded), without spreading to (or from) another part of the building.

**Fire detector**
Device which give a signal in response to certain physical and /or chemical changes accompanying a fire.

**Fire door**
A door or shutter, which, together with its frame and furniture as installed in a building, when closed is capable of meeting specified performance criteria.
**Fire exposure**
Thermal actions affecting the product.

**Fire hazard**
The potential to lose a life (or injury) and / or damage a property by fire.

**Fire resistance**
The ability of an element of a building construction to fulfil for a stated period of time the required load bearing function, integrity and / or thermal insulation specified in the standard fire resistance test.

**Fire risk level**
A function relating to the probability of fire causing a loss of life (or injury) and / or damage the property and the degree of harm caused.

**Fire safety installations**
Those installations concerned with services, alarm and detection, installations for means of escape, suppression and fire fighting equipment.

**Fire scenario**
A qualitative description of the course of a fire with time, identifying key events that characterise the fire and differentiate it from other possible fires It typically defines the ignition and fire growth process, the fully developed stage and the decay stage, together with the building environment and systems that will impact on the course of the fire.

**Fire separating walls**
A wall which separates two adjoining fire compartments.

**Hazard analysis**
Analysis carried out in order to evaluate the potential for loss of fire or injury and / or damage to the property.

**Heat Release Rate**
It is the rate at which the combustion reactions produce heat. The term burning rate is also often found. The heat release of a burning item is measured in kilowatts (kW).

**Ignition**
Initiation of combustion.

**Smoke**
A visible suspension of a solid and /or liquid particles in gases resulting from combustion.

**Smoke control door**
Door set designed to reduce the rate of spread or movement of smoke during the fire.
4 Engineering approach: evaluation of fire resistance of structures

4.1 General
The first step is to identify those that are fire scenarios that can put more crisis in the structural stability and then evaluate them through the use of simulation software. The output of such software will be the natural fire curve that can more probabilistically be produced in the compartment under study. The fire curve will be the thermal stress to be used on the structural elements exposed in order to evaluate the resistance characteristic of the structures.

4.2 Calculation of the natural curve of fire
4.2.1 Fire scenario selection
Considering natural fires, the identification of the possible scenarios that characterize a fire is the most important aspect. Once you have determined the various project scenarios, they will be used for the study of natural fire. Each fire scenario represent a unique combination of events, over which a particular set of conditions associated with security measures. These conditions will be defined in the design fire, while the combination of events is what you need to specify to characterize the scenario. A fire scenario therefore represents a particular combination of events associated with non-project factors such as:
- type of fire (located, fully developed ...);
- terms of ventilation;
- status of each measure of fire safety, including measures of active and passive protection;
- distribution and type of combustible materials;
- detection systems, alarm and extinguishing the fire by means of automatic or manual;
- state of the openings;
- etc.

The fire scenarios determination should be made according to the three main characteristics on which is based the choice:
- building features;
- design fire;
- characteristics of the occupants of the building (if relevant to the scenario);

Building Features
In relation to the characteristics of the building must be evaluated the following parameters:
- the characteristics of the materials;
- the nature and composition of the fuel material and / or flammable;
- the geometry of the environment;
- the type of structure;
- the use of the building;
- the ventilation (natural or mechanical);
- the initial state of the ventilation openings.

The basic parameters are the ventilation, because it determines the possibility or less that the fire reaches the flash over, and the partitioning, since it determine the spread of the fire and the distribution of the fire load.
The ventilation level imposes an upper limit to the burning rate. If the available ventilation is restricted, the fire cannot reach the flashover. In some cases it can be self-extinguishing. Where flashover does occur, the heat release rate rises to the maximum possible with the available ventilation.

If there are different possible openings combinations (e.g. some doors open, some doors closed), options which are most conducive to fire spread should be considered, i.e. a worst case scenario. The assumption that all openings are initially open is not necessarily the worst case. The following parameters should be considered:

- doors should be assumed open if the enclosure has no other openings;
- doors should be assumed closed if the enclosure has other openings;
- all enclosure surfaces (including glazed ones) may be assumed to be imperforate for the duration of the fire if analysis has shown that the conditions have not created openings;

The distribution of the fire load is important because it determines whether it should be considered a scenario of a fire extended to the whole room or a scenario of a localized fire on a portion of the same. The following could be other relevant aspects:

- during the pre-flashover stage, the horizontal and vertical surfaces immediately surrounding the fire should be considered as the enclosure. Moreover openings, although immediately and directly open to the passage of fire and heat, may be characterized as part of the boundaries.
- After flashover, solid boundaries may be assumed to remain intact until no openings are created in the surfaces due to their mechanical response on exposure to fire.
- As the definition of the enclosing surfaces is changed by the creation of openings, the fire conditions might need to be re-examined and fire spread routes re-evaluated.

Design may be simplified by assuming that the compartment is bounded only by those surfaces that have a specific fire resistance: intermediate boundaries without determinate fire resistance are ignored. Anyhow, the possibility of more severe fire conditions developing locally within the compartment need not be considered.

**Design fire**

The design fire should consider very different aspects, such as:

- quantity and nature of the fuel material;
- the role of ventilation;
- geometric characteristics;
- source of ignition;
- growth rate;
- attainment of flashover
- development
- extension
- curve of heat release rate.

They are set on the basis of engineering considerations, such as an event that puts in crisis the stability of a pillar that can be made of steel or reinforced concrete.

When making assessments on the scenarios, the hierarchy of strength of structural elements (node, beam, column) is taken into account, then one of the main considerations is definitely the one to determine which are the weak points of structure.
4.2.2 Determination of the corresponding design fires

Following identification of the design fire scenarios, it is necessary to describe the assumed characteristics of the fire on which the scenario quantification will be based. These assumed fire characteristics are referred to as “the Design fire”.

First of all, it needs to be understood that the design fire is unlikely to occur in practice. Real fires are likely to be less severe and will not necessarily follow the specified design curve, such as a particular heat release rate curve. The design fire quantification process should thus result in a design profile that is conservative.

Design fires are usually characterised by the following variables with respect to time (as needed by the analysis):
- heat release rate;
- fire size (including flame length);

The design fire describes in function of time the progress of the fire in terms of heat release or the amount of released kW (thermal power) per unit time (sec).

Other variables such as temperature, emissivity and location may be required for particular types of numerical analysis.

It is possible to have more than one design fire for a particular fire scenario. For example, when fire spreads beyond the room of fire origin, a new design fire may be required to represent the fire in the second enclosure.

Fire may grow from ignition time through to a fully developed stage and finally decay and eventually burn out. The fire is described by the value of the above variables.

A full specification of a design fire (see Figure 2) may include the following phases:
- incipient phase – characterized by a variety of sources, which may be smouldering, flaming or radiant;
- growth phase – covering the fire propagation period up to flashover or full fuel involvement;
- fully developed phase – characterized by a substantially steady burning rate as may occur in ventilation or fuel-bed-controlled fires;
- decay phase – covering the period of declining fire severity;
- extinction – when there is no more energy being produced.

![Figure 2: HRR curve (source: ISO TR 13387-2 “Design fire scenarios and design fires”)](image-url)
The curve represented in the image represents a generic CURVE HRR which describes the behaviour of a fire from the phase of ignition until the power off. It returns the thermal power expressed in kW (Y-Axis) as a function of time (x-axis).

**HEAT RELEASE RATE**
The HRR curve is determined as a function of the parameters influencing the fire itself i.e.:
- Type and amount of combustible material;
- Position and size of the ventilation openings;
- Rate of fire development.

A more careful study of the materials inside the building subject of assessments will provide a more accurate real curve of heat release of the fire.

The HRR curve is calculated as a function:
- of the combustible materials present in the building or area in which they are made
- of the evaluations (fire load),
- of the ventilation inside the room,
- of the size of the enclosure.

Once determined the specific fire load and the total heat energy released by the fire, as a function of the ventilation openings, is determined if the fire reaches the point of flashover. Determined the point of flashover is calculated the maximum value of thermal power released through the fire of functions that can be found in literature.

Last data necessary for the determination of a natural curve of fire is the speed of development. Literature specifies these values:
- Slow $\alpha = 0.00278 \text{ [kJ/s}^3\text{]}$
- Medium $\alpha = 0.01111 \text{ [kJ/s}^3\text{]}$
- Fast $\alpha = 0.04444 \text{ [kJ/s}^3\text{]}$
- Ultra-fast $\alpha = 0.17778 \text{ [kJ/s}^3\text{]}$

The value influences the slope of the curve in its initial portion until it is reached the full development of the fire, as the assumption of a trend of the fire according to the report $\alpha t^2$ where $t$ represents time.

Once you have significant data such as the maximum energy of the fire developed, the maximum thermal power developed and the speed of fire development, the HRR curve can be traced.

**Calculation procedure**
The effects that causes a fire inside a building are necessary for the assessment of the fire hazard to materials and structures present. These effects depends on the value assumed by the thermal power released by the fire, therefore it's very important to carry out an estimation of its variation over time.

Known facts are:
- Dimensions of the local geometric;
- Dimensions of the ventilation openings;
- Distribution type, calorific value and quantity of the combustible material;
- Specific value of the fire load [MJ/m$^2$] in the enclosure surface.

One of the most common procedures includes:
1. Evaluate the minimum value of $HRR_f$ expressed in [kW] that can cause flashover through the use of technical literature expressions (e.g. Thomas, Babrauskas or EC1).
2. Assume a trend of the thermal power according to the square of the time compared to a constant to determine the time required to reach the point of Flashover:

\[ t_f = \left( \frac{\text{HRR}_f}{\alpha} \right)^{1/2} \]

3. Compare the value of the energy developed to flashover with the total energy available as a result from the fire load to verify if the fire can pass to the stage of full development.

4. Calculating the maximum value of the thermal power \( \text{HRR}_{\text{max}} \) in relation to the surface of ventilation; Determination of the time \( t_a \) needed to reach the full development of the fire;

5. Determination of the time interval \( (t_b-t_a) \) where the fire appears to be at the stage of full development. As prescribed in ISO TR 13387-2 energy developed from the start of the fire until the end of the stage of full development is equal to 80% of total energy;

6. Determination of the time \( t_c \) in which happens extinguish fire and in this phase is produced energy equal to 20% of that total.

At this point you can draw the curve on the fire HRR project that has been selected with the study of the design fire scenarios.

![HRR Curve](image)

Technical literature also provides other procedures, which may include simpler methods. For example it can be assumed that a curve uses the relationship \( \alpha t^2 \) until reaching the maximum power, or a relationship that does not take into account the initial growth phase, etc.

The applicability of the method for the definition of the curve HRR must be evaluated case by case.

### 4.2.3 Effects of fire protection systems. An examples: sprinklers

The time to control a fire is related to the time required to activate the protection systems and to the time required to stop further fire growth. The time for activating a suppression systems can be estimated using fire detection. The time for effective fire control is not easy to determine and, therefore, the fire safety designer should use conservative estimates for this time.

For example, some analytical suppression models of automatic fire sprinklers have been developed in office fire scenarios.

The reduction of heat release rate, in the case where the sprinkler can effectively suppress the fire, can be estimated by one of the following equations:
where:

\[ Q(t-t_{\text{act}}) = \text{heat release rate after the activation time, [kW]}; \]
\[ Q(t_{\text{act}}) = \text{heat release rate at the activation time, [kW]}; \]
\[ t = \text{any time following activation, [s]}; \]
\[ t_{\text{act}} = \text{time of activation of sprinkler, [s]}; \]

- Equation by Fleming (1993)

where:

\[ w = \text{spray density, mm/s}. \]

The estimation of the reduction of the heat release calculated with the formulas above is good, except in the case of shielded fires. A study to investigate the probability of occurrence and expected size of shielded fires in sprinklered buildings indicated that shielded fires continue to burn for some time before the heat release rate begins decreasing.

The results of the study show that, although the fire was controlled by sprinklers, a steady heat release rate of up to 100 kW can be sustained after the activation of sprinklers.

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

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

b) the application of the extinguishing agent halts the increase in the rate of heat release, and the fire then continues to burn at a constant rate; In some design applications, it is typical to assume that the fire is steady state from ignition.

c) fire continues to grow but more slowly than before ;

d) fire is suddenly reduced in rate of heat release, but continues to grow more slowly ;

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

Similar assessments can be made for the other protection systems (smoke and heat exhaust systems, gas extinguishing systems, etc.).

4.2.4 Choice of the simulation model of fire

Fire modelling can be grouped into two categories: probabilistic or stochastic fire models and deterministic fire models

Probabilistic fire models involve the evaluation of the risk based on the probabilities evaluation of all the parameters influencing the fire, such as formation of openings and distribution of fuel load in the compartment of fire origin.
The probabilities are usually time dependent and are determined through experimental data and fire incident statistics. Laws of physics are generally not included in the equations used by the models. The results of the models are in terms of probabilities including fire likelihood. Deterministic fire models are typically based on physical, chemical and thermodynamic relationships, with empirical or analytical correlations used to calculate the impact of fire. Deterministic models can be very simple requiring a short computing time or highly complex requiring hours of computation. Typically, deterministic models can be classified as:
- zone models
- fields models.

There is no fire model that is comprehensive for all fire applications. The selection of a fire model depends on a number of factors including understanding the limitations and assumptions used in the model, validation of the model, documentation accompanying the model and ease of use. Computer fire models should be carefully selected. To make the right decision in the selection process, the issue of the validation of the fire model must be addressed. The results of the model must be compared against experimental data to determine the predictability of the model. In addition, the model should be checked against simple hand calculations for consistency between input and output. Finally, the result should be verified using the judgement of an experienced fire protection engineer.

The documentation accompanying the model provides a good indication of the quality of the model. It should include the technical documentation for the model and a guide on how to use the model. The technical documentation includes the computer software (source code, if available, and information regarding installation of the model) and the theoretical basis for the calculations. The latter can be used to determine the level of confidence which can be placed in the fire model. When using a fire model, it is recommended to determine the sensitivity of the output data to changes in the input ones. This to verify if changes in the data or the model assumptions and applicability will lead to a different decision. The sensitivity analysis will determine the most dominant and significant variables. It also will determine if the user should pay careful attention to particular input values that might significantly affect the results.

Fire engineering models can provide a good estimate of the effects of fire, however, the randomness of fire is such that the results may not be precise. When a user has some doubts about a model, the user should establish from the literature (especially experimental research) the appropriateness of the results of the model. Further, when dealing with uncertainty associated with data for models, it is usually required to apply adequate factors of safety to ensure a conservative design. Furthermore, when uncertainty exists, it is appropriate to conduct a sensitivity analysis.

**Zone models**
The theory of the ‘zonal’ approach in confined spaces was applied to fires by several groups since the 1970s, e.g. Zukoski. Zone models are one dimensional or bi-dimensional models which divide a compartment with a relatively enclosed volume into a number of distinct zones. In most applications, the volume is not totally enclosed as doors, windows, and vents are usually included in the calculation. Each zone is considered homogeneous and is characterized by a set of time-dependent parameters describing its physical state. The number of zones ranges typically from one to five. Possible zones include the hot layer, the cool layer and the rising thermal plume and ceiling jet.
The enclosure usually is divided into two distinct zones: the hot upper smoke layer and the lower layer of cooler air. The plume acts as an enthalpy pump between the lower layer and the hot upper smoke layer. Within each of these zones, the pertinent conservation laws (i.e. mass and energy), in the form of mathematical equations are solved to describe the conditions of interest.

In reality, depending on the room size and heat release rate of the fire, there is a non perfectly defined ‘interface’ between the hot upper smoke layer and lower layer.

The upper smoke layer is not at uniform temperature (as higher temperatures are observed closer to the fire and plume); however, the use of two uniform zones allows for reasonable approximations of the development of a fire in an enclosure under many conditions.

Zone models for compartments have been developed for both single-room and multiroom configurations. They are easy and practical to use, and fast to run. Because of their simplicity, zone models can achieve first order approximations to real fire behaviour. The accuracy may, however, suffer in predicting complex fire situations. Table 1 lists the zone models which have been identified:

<table>
<thead>
<tr>
<th>Model</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGOS</td>
<td>DENMARK</td>
<td>Multicompartment zone model</td>
</tr>
<tr>
<td>ASET</td>
<td>US</td>
<td>One room zone model with no ventilation</td>
</tr>
<tr>
<td>ASET-B</td>
<td>US</td>
<td>ASET in Basic instead of Fortran</td>
</tr>
<tr>
<td>BRANZFIRE</td>
<td>NEW ZEALAND</td>
<td>Multiroom zone model, including flame spread, multiple fires, and mechanical ventilation</td>
</tr>
<tr>
<td>BRI-2</td>
<td>JAPAN/US</td>
<td>Two-layer zone model for multistory, multicompart ment smoke transport</td>
</tr>
<tr>
<td>CALTECH</td>
<td>JAPAN/US</td>
<td>Preflashover zone model</td>
</tr>
<tr>
<td>CCFM.VENTS</td>
<td>US</td>
<td>Multi-room zone model with ventilation</td>
</tr>
<tr>
<td>CFAST/FAST</td>
<td>US</td>
<td>Zone model with a suite of correlation programs - CFAST is the solver, FAST is a front-end</td>
</tr>
<tr>
<td>CFIRE-X</td>
<td>GERMANY</td>
<td>Zone model for compartment fires, particularly liquid hydrocarbon pool fires</td>
</tr>
<tr>
<td>CiFi</td>
<td>FRANCE</td>
<td>Multiroom zone model</td>
</tr>
<tr>
<td>COMPBRN-III</td>
<td>US</td>
<td>Compartment zone model</td>
</tr>
<tr>
<td>COMF2</td>
<td>US</td>
<td>Single room postflashover compartment model</td>
</tr>
<tr>
<td>DACFIR-3</td>
<td>US</td>
<td>Zone model for an aircraft cabin</td>
</tr>
<tr>
<td>DSLAYV</td>
<td>SWEDEN</td>
<td>Single compartment zone model</td>
</tr>
<tr>
<td>FASTlite</td>
<td>US</td>
<td>Feature limited version of CFAST</td>
</tr>
<tr>
<td>FFM</td>
<td>US</td>
<td>Preflashover zone model</td>
</tr>
<tr>
<td>FIGARO-II</td>
<td>GERMANY</td>
<td>Zone model for determining untenability</td>
</tr>
<tr>
<td>FIRAC</td>
<td>US</td>
<td>Uses FIRIN, includes complex vent systems</td>
</tr>
<tr>
<td>FireMD</td>
<td>US</td>
<td>One room, two zone model</td>
</tr>
<tr>
<td>FIREWIND</td>
<td>AUSTRALIA</td>
<td>Multiroom zone model with several smaller submodels (update of FIRECALC)</td>
</tr>
<tr>
<td>FIRIN</td>
<td>US</td>
<td>Multiroom zone model with ducts, fans, and filters</td>
</tr>
<tr>
<td>FIRM</td>
<td>US</td>
<td>Two zone, single compartment model</td>
</tr>
<tr>
<td>FIRST</td>
<td>US</td>
<td>One room zone model, includes ventilation</td>
</tr>
</tbody>
</table>
In one-zone models is considered a uniform distribution of the gas temperature in the whole compartment. This distribution is typical of fires in the post flash over where the mixing of the flue gas is such as to justify the assumption of a single temperature value for the entire compartment. As well as the evolution of the fire you can go from a pre-flashover to a post-flashover also in modeling should be able to switch from a two-zone model to a model to a zone.

**Computational fluid dynamic models**

Field models are two-dimensional or three-dimensional models. In these models the compartment is divided into a grid of small volume elements (on the order of thousands or hundreds of thousands), in which the governing equations for mass, momentum and energy are solved for each control volume. This allows for a more detailed solution compared to zone models: field models can calculate the variables (e.g. temperature) at the point in a compartment.

Because there are more than two uniform zones, a field model can be appropriate for more complex geometries where two zones do not accurately describe the fire phenomenon. They can also be used for outdoor fires such as large fuel tank fires.

These models provide very detailed solutions, but require detailed input information, and usually require more computing resources.

This can create a costly time delay in obtaining a solution while zone models usually provide a solution more quickly. This trend of increasingly growing numbers of field models stems from improved computer hardware which allows for faster, more complex computational techniques. Table 2 lists the field models which have been identified.

<table>
<thead>
<tr>
<th>Model</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOFT-FT</td>
<td>US</td>
<td>Smoke movement from large outdoor fires</td>
</tr>
<tr>
<td>CFX</td>
<td>UK</td>
<td>General purpose CFD software, applicable to fire and explosions</td>
</tr>
<tr>
<td>FDS</td>
<td>US</td>
<td>Low Mach number CFD code specific to fire-related flows</td>
</tr>
<tr>
<td>FIRE</td>
<td>AUSTRALIA</td>
<td>CFD model with water sprays and coupled to solid/liquid phase fuel to predict burning rate and extinguishment</td>
</tr>
<tr>
<td>FLUENT</td>
<td>US</td>
<td>General purpose CFD software</td>
</tr>
<tr>
<td>JASMINE</td>
<td>UK</td>
<td>Field model for predicting consequences of fire to evaluate design issues (based on PHOENICS)</td>
</tr>
<tr>
<td>KAMELEON FireEx</td>
<td>NORWAY</td>
<td>CFD model for fire linked to a finite element code for thermal response of structures</td>
</tr>
<tr>
<td>KOBRA-3D</td>
<td>GERMANY</td>
<td>CFD for smoke spread and heat transfer in complex geometries</td>
</tr>
<tr>
<td>MEFE</td>
<td>PORTUGAL</td>
<td>CFD model for one or two compartments, includes time-response of thermocouples</td>
</tr>
</tbody>
</table>
4.2.5 Output from simulation models: the natural fire curve

The natural curve of fire determined based on models of fire and physical parameters that define the state variables of the fire compartment, describes the thermal stress for the structures into the compartment itself. This is the main parameter that must be determined to assess the fire resistance in real fires, and it is the input data for the mechanical analysis procedures explained in section 1.2.3.

These procedures refer to the following Eurocodes standards:

- **EN 1991-1-2** Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire. It deals with thermal and mechanical actions on structures exposed to fire, contains thermal actions related to nominal and physically based thermal actions and gives general principles and application rules in connection to thermal and mechanical actions.

- **EN 1992-1-2** Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design. It deals with the design of concrete structures for the accidental situation of fire exposure. It only identifies differences from, or supplements to, normal temperature design and covers only passive methods of fire protection. This part gives principles and application rules for designing structures for specified requirements in respect of the required functions and the levels of performance.

- **EN 1993-1-2** Eurocode 3: Design of steel structures – Part 1-2: General rules – Structural fire design. It deals with the design of steel structures for the accidental situation of fire exposure and consider only passive methods of fire protection. EN 1993-1-2 applies to steel structures and gives principles and application rules for designing structures for specified requirements in respect of the load bearing function and the levels of performance.

- **EN 1994-1-2** Eurocode 4: Design of composite steel and concrete structures – Part 1-2: General rules – Structural fire design. It deals with the design of composite steel and concrete structures for the accidental situation of fire exposure and only identifies differences from, or supplements to, normal temperature design. This Part 1-2 of EN 1994 deals only with passive methods of fire protection, and gives principles and application rules for designing structures for specified requirements in respect of the required functions and levels of performance.

- **EN 1995-1-2** Eurocode 5: Design of timber structures – Part 1-2: General rules – Structural fire design. It deals with the design of timber structures for the accidental situation of fire exposure and only identifies differences from, or supplements normal temperature design. This part deals
only with passive methods of fire protection, and gives principles and application rules for designing structures for specified requirements in respect of the required functions and levels of performance.

**EN 1996-1-2** Eurocode 6: Design of masonry structures – Part 1-2: General rules – Structural fire design. It deals with the design of masonry structures for the accidental situation of fire exposure, and only identifies differences from, or supplements to, normal temperature design. This part deals only with passive methods of fire protection, and gives principles and application rules for designing structures for specified requirements in respect of the required functions and levels of performance.

**EN 1999-1-2** Eurocode 9: Design of aluminium structures – Part 1-2: General rules – Structural fire design. It deals with the design of aluminium structures for the accidental situation of fire exposure and only identifies differences from, or supplements to, normal temperature design. This part deals only with passive methods of fire protection, and gives principles and application rules for designing structures for specified requirements in respect of the required functions and levels of performance.

Below is an example of a time-temperature curve characteristic of a real fire.

![](image)

**4.3 Approach to the calculation of the mechanical behaviour of structures exposed to fire**

The fire behaviour of structures using a fire natural curve can be calculated in the manner described by the Structural Eurocodes (see chapter 1.2). The assessment of the fire resistance as required by the Structural Eurocodes can be carried out in different ways:

1. by checking a single structural element;
2. by evaluating a substructure (reinforced concrete frame, etc.);
3. by checking the entire structure

The resistance is calculated by applying the natural curve of fire, determined as described in the previous chapters, usually with the aid of structural finite element models.

By using structural software and then advanced models there are no theoretical limitations neither with regard to the type of fire, nor to the degree of complexity of the structure. They may also consider the effects due to the thermal actions contrasted, the redistribution of the effects since you treat statically indeterminate structures.

The annex to this document illustrates a developed case study as an example.
5 Conclusions
The use of a performance approach responds to the need to achieve more economic structures at the same level of security, using the technological developments produced by simulation software and increased computing capacity.
The use of natural fire curves which take into account all the geometric and architectural characteristics, the possible fires that can be developed and the safety measures present (plant engineering and management), allows a more efficient design of buildings.
The analysis leads to a deep understanding of the entire project to assess in quantitative terms the effects the security measures in order to their optimization.
The result is the achievement of a security level equivalent to that which would have been obtained proceeding with the prescriptive approach, with a better management of resources and thus with a possible significant reduction in costs.

6 Bibliography
For the preparation of this guideline, the following documents have been used:
- EN 1991-1-2 – Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire
- PD 7974-3:2011: “Application of fire safety engineering principles to the design of buildings. Structural response and fire spread beyond the enclosure of origin”