INTERNATIONAL STANDARD

ISO 18195

First edition
2019-02

Corrected version
2019-03

Method for the justification of fire partitioning in water cooled nuclear power plants (NPP)

Méthode de justification de l'efficacité de la sectorisation incendie des centrales nucléaires utilisant l'eau comme fluide caloporteur

Reference number
ISO 18195:2019(E)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 6, *Reactor Technology*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This corrected version of ISO 18195:2019 incorporates the following corrections:

— In 5.4.5.4, a few formatting corrections were made;

— In 6.4.7, Figure 13 has been corrected and the key modified accordingly.

Introduction

This document is intended to provide a technical specification to verify the adequacy of the performance of fire partitions in nuclear power plants. The intended audience of this document are fire safety engineers and project designers. Nuclear authorities are also concerned considering that this method is to be used in the process of fire hazard nuclear safety demonstration. The method presented herein includes a combination of standardized testing and ad hoc testing with numerical and empirical calculations. Users of this document are expected to be appropriately qualified and competent in the fields of fire safety engineering, risk assessment and fire resistance standardization.

This document specifies a new methodology to Nuclear Power Plant (NPP) designers, fire safety professionals and nuclear safety authorities. This methodology aims to verify the adequacy of the performance of fire barriers in nuclear power plants in order to avoid fire propagation. This method is a potential tool for risk-informed, performance-based assessment.

NOTE This method is based on the EPRESSI method developed by EDF in collaboration with Efectis France fire safety laboratory in France for EPR reactors[39].

Method for the justification of fire partitioning in water cooled nuclear power plants (NPP)

1 Scope

The document provides:

— guidelines for determining the thermal effects to consider on fire barriers inside a given room;

— guidelines for determining the global performance of the fire barriers based on standard test characterization;

— guidelines for assessing the need for additional tests to verify the robustness of the solution.

Requirements of applicable standards, numerical tools validation and verification (V&V), and the expected qualification of fire resistance laboratories are detailed.

The limitations of the method's applicability and scope are discussed.

The purpose and justification of this document is to describe a new methodology for the verification of the efficiency of fire barriers, which is initially based on a standardized fire resistance test.

The significance of this work relates to the fact that the present methodology will enhance the level of safety by providing more realism to hazards analysis in combination with standardized test data. It completes the standard ISO-fire rating required for justifying the performance.

The most relevant benefit of this method concerns the determination of the global performance of a barrier in a fire of extended duration compared to the classification given by the ISO-fire rating.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12749-2, *Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 2: Radiological protection*

ISO 12749-3, *Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 3: Nuclear fuel cycle*

ISO 12749-4, *Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 4: Dosimetry for radiation processing*

ISO 12749-5, *Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 5: Nuclear reactors*

ISO 13943, *Fire safety — Vocabulary*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 13943, ISO 12749-2, ISO 12749-3, ISO 12749-4, and ISO 12749-5 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1 Terms and definitions

3.1.1
credited combustible
part of the potential combustible material that will actually participate to the fire development

3.1.2
design basis fire
fire which may break out in any fire source of the plant and which has the severest consequences (duration, severity)

Note 1 to entry: For a given room, it is a fire taking into account all available fuel in this room liable to burn. Its characteristics are calculated taking into account the characteristics of the rooms and fuels.

3.1.3
fire volume
volume inside a building, composed or one or several rooms and designed to prevent the extension of a fire through its boundaries

Note 1 to entry: One of the means of preventing the extension of the fire is to keep it within a limited volume, either physically, by partitions opposing the fire propagation, either spatially, by boundaries associated with the remoteness of the components, with active protection systems (sprinklers), or with passive protection systems (structural features, cable wraps).

3.1.4
fire cell
fire volume (3.1.3) consisting of one or more rooms, bounded by separations guaranteeing that a fire occurring inside cannot extend to the outside or that one occurring on the outside cannot spread to the inside for a given period of time

Note 1 to entry: The boundaries of a fire cell may be either fire-resistant physical barriers, wall, ceiling and floor or *spatial separation* (3.1.15) through openings with a certain configuration and distance rules between combustible sources guaranteeing geographical separations with adjacent rooms and other fire areas. The non-propagation assumption has to be verified (by fire influence studies).

3.1.5
fire compartment
fire volume (3.1.3) consisting of one or more rooms, bounded by material *partitions* (3.1.10) whose fire resistance guarantees that a fire occurring inside cannot extend to the outside or that one occurring on the outside cannot spread to the inside for a given period of time

Note 1 to entry: All the partitions of a fire compartment shall be fire-resistant physical barriers, walls, ceilings, or floors.

3.1.6
fire resistance rating
time during which the fire *partitioning elements* (3.1.9) (partitions, walls, floors, doors, dampers, caulking of penetrations, enclosures of cable racks, etc.) can fulfil their assigned role, despite the effect of a standard fire

3.1.7
low heat load threshold
LHLT
threshold which is introduced to avoid calculations in case of rooms that have too small quantity of combustible material and are neither PFL nor PFG

Note 1 to entry: See 5.4.5.3.

3.1.8
"neither PFG nor PFL" criterion
criterion that is met when the quantity of combustible material is not sufficient to generate a significant fire and does not present risks for spreading to secondary fire sources

Note 1 to entry: By extension, a room is said to be "neither PFG nor PFL" when the concentration of combustible masses in it is not enough to generate a widespread fire (with no necessity of further verification).

3.1.9
partitioning elements
features (partitions, fire walls, ceilings, floors, ducts, seals of openings such as doors, shutters, dampers, hatches as well as seals of cable bushings and piping sleeves) which make up a *partition* (3.1.10)

3.1.10
partition
set of *partitioning elements* (3.1.9) which fully bound the relevant area by *physical separation* (3.1.13)

3.1.11
possibility of a fire getting generalized
PFG criterion
criterion for a fire source when its burning is likely to result in flashover and a generalized fire

Note 1 to entry: By extension, a room is said to be PFG when a fire breaking out in an unfavourable part of the room may result in flashover and generalized fire in the whole room.

3.1.12
all possible fires remaining localized
PFL criterion
criterion for a fire source when its burning shall not result in flashover or propagate to other parts of the *room* (3.1.14)

Note 1 to entry: A fire meeting this criterion remains localised and goes out spontaneously. By extension, a room is said to be PFL when a fire breaking out at the most unfavourable part of the room cannot result in flashover nor propagate to other parts of the room; it remains localised and goes out spontaneously.

Note 2 to entry: The hypothesis of a fire source or room being PFL assumes a single fire source representation but the non-propagation to other fire sources inside or outside the room need a confirmation using a spread temperature threshold (STT).

3.1.13
physical separation
installation of two items of equipment in two distinct *rooms* (3.1.14) of which at least one is inside a *fire compartment* (3.1.5), or protection of one of them by an insulating thermal casing to prevent the simultaneous loss of both items of equipment due to a single fire

3.1.14
room
<common meaning> single volume identified by the user inside the building with no structural separation assumed inside

Note 1 to entry: Its boundaries may or may not be completely closed.

3.1.15
spatial separation
installation of two items of equipment in different *rooms* (3.1.14) or at an adequate distance free of any fuel to prevent fire from spreading

3.1.16
spread temperature threshold
STT
threshold that is considered in the method to determine if there is a risk of spreading of a PFL fire source into a PFG fire source

Note 1 to entry: The STT applies to the hot gas layer (see 5.4.5.4).

3.1.17
standard time temperature curve
temperature-time curve used for the relevant fire resistance standard tests

Note 1 to entry: In the scope of document, this curve is defined according to ISO 834-1:1999, Figure 7. The curve follows the Formula $T = T_0 + 345 \log(8t + 1)$ with t the time (min) and T_0 the initial temperature.

3.2 Symbols

Symbol	Meaning	Unit
A	surface (structures)	m^2
Ao_i	surface of the vertical opening *i* of the room	m^2
AT	total surface of the walls of the room (excluding surface of openings)	m^2
β_1, β_2	pyrolysis rate coefficients	$kg{\cdot}s^{-1}$
α	growth factor (heat release rate)	$kJ{\cdot}s^{-3}$
D	equivalent diameter: $D = \sqrt{4S/\pi}$	m
Ho_i	maximum height of the vertical opening *i* of the room = distance between the top of the opening and the floor of the room	m
ΔH_C	heat of combustion of a fuel	$kJ{\cdot}kg^{-1}$
$K\beta$	product of the extinction coefficient of the flame *K* and a correction factor β	m^{-1}
L	length of the rack	m
M	mass of combustible cables	kg
$\dot{m}$	mass loss rate (= rate of pyrolysis)	$kg{\cdot}s^{-1}$
$\dot{m}_{max}$	maximum mass loss rate: $\dot{m}_{max} = \frac{\dot{Q}_{max}}{\Delta H_C}$	$kg{\cdot}s^{-1}$
n_{rack}	number of racks	
$\dot{Q}$	heat release rate	kW
$\dot{Q}_{max}$	maximum heat release rate of the fire source	kW
S	surface (liquid pool)	m
S_t	stoichiometric ratio of a fuel	g_{o2}/g_{fuel}
t	time	s
t_d	Time where the performance curve starts to decrease	s or h
T, θ	temperature	°C or K
T_0	initial ambient temperature	°C or K

Symbol	Meaning	Unit
T_{cor}	correlated temperature gap estimated in the process of material behaviour modelling.	°C or K
$T_{num,i}$	calculated temperature at point "*i*" (*i* is an occurrence of experiment/calculation comparison : instant, location)	°C or K
$T_{exp,i}$	experimental temperature at point "*i*".	°C or K
T_{max}	Maximum temperature at time t_d for a performance curve	°C or K
ΔT_{local}	gap of temperature from initial temperature at a certain location (defined by the applied standard) during a fire resistance test	°C or K
$\Delta T_{average}$	gap of an average temperature (defined by the applied standard) from initial temperature during a fire resistance test	°C or K
$\theta_g(t)$	temperature condition at time *t*, following an increase law for material performance	°C
ε	emissivity: $\varepsilon_{material}$: emissivity of a material surface. $\varepsilon_{furnace}$: emissivity of a furnace surface	—
X_{O2}	oxygen ratio in the entering air	g_{o2}/g_{air}

3.3 Abbreviated terms

CFD	computational fluid dynamics
HRR	heat release rate
MLR	mass loss rate
MQH correlation	MacCaffrey - Quintiere - Harkleroad correlation
NPP	nuclear power plant
UL	underwriters laboratories

4 Method for justification of nuclear safety fire partitioning: global approach

4.1 Objective of the method

The present method is a tool made available for engineers to check whether the fire resistance performance of the fire partitioning elements in buildings is adequate to resist the design basis fire to which they could be exposed, independently of manual firefighting considerations.

As a prerequisite, prevention against the risks of fire in PWRs is based on the principle of separation of buildings into fire volumes, which are bounded by fire resistant walls. First, the fire protection design basis shall establish the minimum fire resistance rating of the fire partitioning elements.

NOTE Numerical values, empirical correlations or mathematical laws can be fixed by the document, recommended with possibility of change (rec.), or given as example (e.g.). If no indication is given, they are considered as fixed.

4.1.1 The basis of design: standard fire resistance tests

The fire resistance rating of fire partitioning elements is determined by a standard test, in accordance with the regulation and with the standardization.

For other products not covered by standard tests, such as fire resistant housings or enclosures, the fire resistance test may be carried out according to specific procedures. Regardless of the test method employed, the thermal stress applied to the product shall be that of the standard time/temperature curve.

The fire resistance rating of a product is based on national, European or International standards or, when no standard applies, on plant designer specifications respecting the same performance criteria considered in similar standards.

- Thermal effects of the standard fire temperature curve.
- Measurement and qualitative systems for the performance criteria check.
- Temperatures: on elements, on exposed and unexposed surface or inside elements: ambient or surface.
- Electrical equipment functionality test system.
- Pilot flames or a layer of cotton for ignition verification.
- Fixed gauge tubes to check openings through the partitioning elements.

Furthermore, these tests require the use of standardized equipment and a description of its support and assembly. Extensions to the performance checks of different products are made on the basis of these references. Each of these criteria and measurements shall be taken into consideration during the analysis of the product in order to build its performance curve (see Clause 6).

NOTE The fire resistance rating of fire partitioning elements is determined by a standard test, in accordance with the regulation and with the standardization. For instance the rating may be given from the decision of European Commission 2000/367/CE and 2003/629/CE. Depending of the country, alternative standards could be used when needed by the Authority Having Jurisdiction.

The performance can concern:

- R: load-bearing capacity;
- E: integrity;
- I: insulation
- C: self-closing;
- S: smoke leakage;
- W: radiation;
- DH: smoke screen.

The rated time is given in minutes. For example, REI 120 refers to a structure which guaranties load-bearing capacity, integrity and insulation for 120 min. These tests are carried out and approvals delivered by a laboratory approved by the national authorities.

4.1.2 Aim, limitations, and precautions

4.1.2.1 Aim

The method applies to fire barriers qualified with a fire resistance standard.

The present methodology can be adapted to any other standard fire temperature curves and testing conditions, such as those specified by ASTM, UL or any national standardized curve used for qualification.

From European or international standardization (ISO 834 or EN 1363) the fire resistance test is based on a standard time/temperature fire temperature curve with a fast temperature rise, representative of flashover conditions in organic solid fires. The temperature increase is represented by the logarithmic curve, following Formula (1):

$$T - T_0 = 345 \log(8t + 1) \tag{1}$$

where

t is the time in min;

T_0 is initial ambient temperature (see Figure 1).

The current methodology extends the performance assessment of a fire resistant product to a longer duration compared to that of the rating assessment. The methodology set up remains within the framework of the fire resistance test, namely a flashover or similar in terms of temperature and pressure distribution.

Unlike the current method of verification of robustness of fire partition elements, it will be the responsibility of the operator to demonstrate that fire resistance tests are representative of operational conditions.

4.1.2.2 Limitations

The aim of the method does not cover certain fire scenarios. For example:

— a fire with a very small heat release rate, in case where the fire barriers includes components likely not to react (e.g.: intumescing elements) or to be activated (e.g.: thermal fuse). Note that additional tests performed at low temperature (see Euroclass "s" classification) may be performed to solve this issue. Of course very small fires are less challenging from a fire hazard point of view and specific demonstration may be proposed for those cases.

— a fire combined with severe pressure conditions (shock wave, blast, etc.): different standards are necessary to evaluate component performance under these conditions.

4.1.2.3 Precautions

Precautions include the following:

— a very fast growth capable of generating thermal shocks greater than those given by the conventional curve (mainly represented by a temperature rise time in °C/min): it can be for example assumed that, based on the recorded sampling time during ISO-fire tests, the maximum temperature rise is limited to 329 °C /min. This should be compared to the maximum temperature increase over 1 minute during the real scenario. Same approach may be performed for any other conventional curves (ASTM, Hydrocarbon, etc.). Nevertheless, this aspect is controlled by the method through the fire temperature curve slope considerations (see 4.2).

— a confined fire excessively ventilated and isolated with a fire load composed on material with high combustion heat is capable to produce very high temperatures (greater than those obtained with the conventional curve during the period tested) : fire behaviour of the partition element in such situation should be assessed using the adapted conventional temperature – time curve. Nevertheless this aspect is controlled by the method through the fire temperature curve maxima considerations (see 4.2).

Additional hose stream tests are sometimes required and are performed at the end of the fire tests for verifying the performance of the products with high-pressure water jet on the exposed phase (for example ASTM E2226[40]). The current methodology is based only on the fire behaviour of the product during the fire test period without taking into account the hose stream tests, which is consistent with the fire resistance ISO standards.

The performance criteria defined for the standard fire resistance rating are also used for assessing performance in the current method. Any adaptation shall be justified.

NOTE The methodology described below is not intended to determine whether a qualification criterion is relevant or not.

4.1.3 Minimum requirements concerning the qualification of the method practitioners

The following method shall be applied by qualified and well-informed practitioners.

The first part of the method (see Clause 5) is appropriate for fire safety engineers with an adequate knowledge of fire safety science and the applicable codes. The organisation shall apply the principles of ISO 9001.

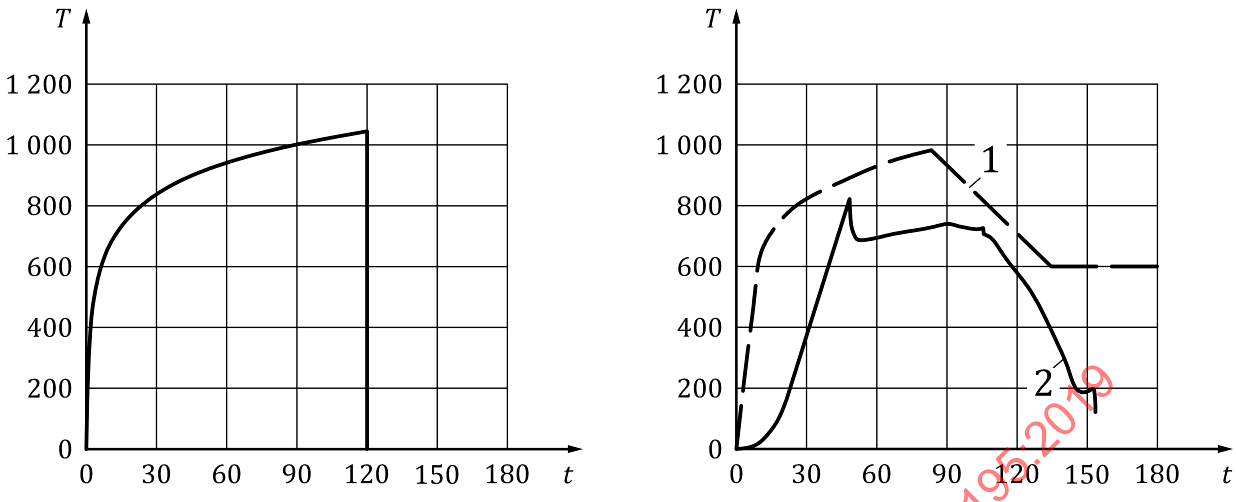
A fire safety laboratory is required for section on determining barrier performance (see Clause 6). As the method requires knowledge and experience not only in the application of standard fire tests, but also in more complex instrumentation processes and engineering models, the capability of the laboratory teams has to be confirmed.

The fire laboratory meet the requirements of ISO/IEC 17025 or an equivalent national alternative for the relevant fire tests.

4.2 General principle of the method

For one room, different design fire scenarios are defined. Each of them leads to one temperature-time curve. The design basis fire temperature curve of the room is a temperature/time curve equal or superior, in each plotted point, to any possible fire conditions concerning the room.

Fire resistance tests are carried out to assess the ability of a given fire barrier to resist the conventional fire (see Figure 1). They do not necessarily reflect its behaviour in a real fire where thermal stress may be, for instance, sharper but shorter or weaker but longer. The present methods consists of creating a set of time/temperature curves that represent the thermal stress a given fire barrier can successfully withstand. This set of curves constitutes the performance diagram of the given fire barrier.



a) ISO 834 (2h rating) **b) Method application**

Key

t time in min

T temperature in °C

1 fire barrier performance curve

2 room fire curve

Figure 1 — ISO 834 versus method application

The method process consists of:

— setting up performance curves for each fire barrier (one or several curves constituting the fire performance diagram of the barrier);

— setting up the design basis fire temperature curve for each room;

— comparing the design basis fire temperature curve of a given room with the performance curves of the fire barriers in the room;

A fire barrier will be qualified for a given room only if all the following criteria are met by at least one performance curve belonging to the fire performance diagram:

— the maximum slope of the fire temperature curve is less than the maximum thermal gradient of the performance curve;

— the area delimited by the fire temperature curve is smaller than the area delimited by the fire resistance performance curve. Qualitatively, this means the heat of the fire is less than the heat the element can withstand;

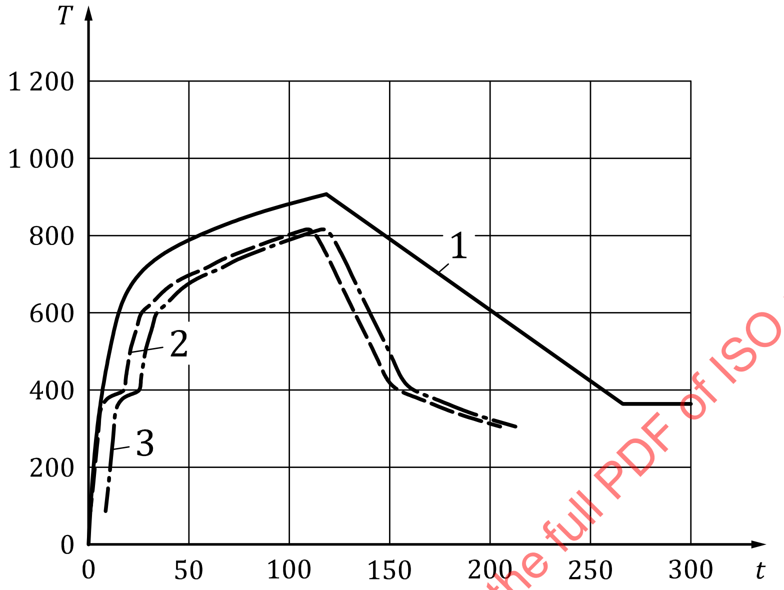
— the maximum temperature of the fire temperature curve is less than the maximum temperature of the fire resistance performance curve.

Considering that the design basis fire temperature curve starts with the growth stage of the fire, which presents the maximum slope, at least one fire resistance performance curve of the equipment shall encompass the fire temperature curve of the room to fulfil these criteria (see Figure 2). If not, the equipment will not be validated for the room and a different strategy will be necessary: choice of an element with better fire resistance properties, addition of other means of protection, elimination of combustible loads in the room, etc.

NOTE 1 When comparing the curves, one can translate the design basis fire temperature curve on the time axis in order to demonstrate that it is below a fire resistance performance curve (see Figure 2). In those cases, one shall be careful to fulfil condition 1.

NOTE 2 The design basis fire temperature curve starts at the temperature of the room in steady state. When the design basis fire temperature curve starts at a higher temperature than an available performance curve, the design basis fire temperature curve will be translated to the right before comparison. As a precaution, the translation will be at least 3 times the minimum translation necessary to ensure the design fire temperature curve start is bounded by the performance curve.

NOTE 3 The role of automatic extinguishing systems in the present method is detailed in 5.4.1 and flowcharts 1 (see Figure 3) and 2 (see Figure 7).



Key

t time in min

T temperature in °C

1 fire barrier performance curve (starting at 20 °C)

2 room fire curve (starting at 40 °C)

3 shifted room fire curve

Figure 2 — Performance curve versus fire temperature curve

4.3 Design of the partitioning: justification of the adequate performance of fire barriers

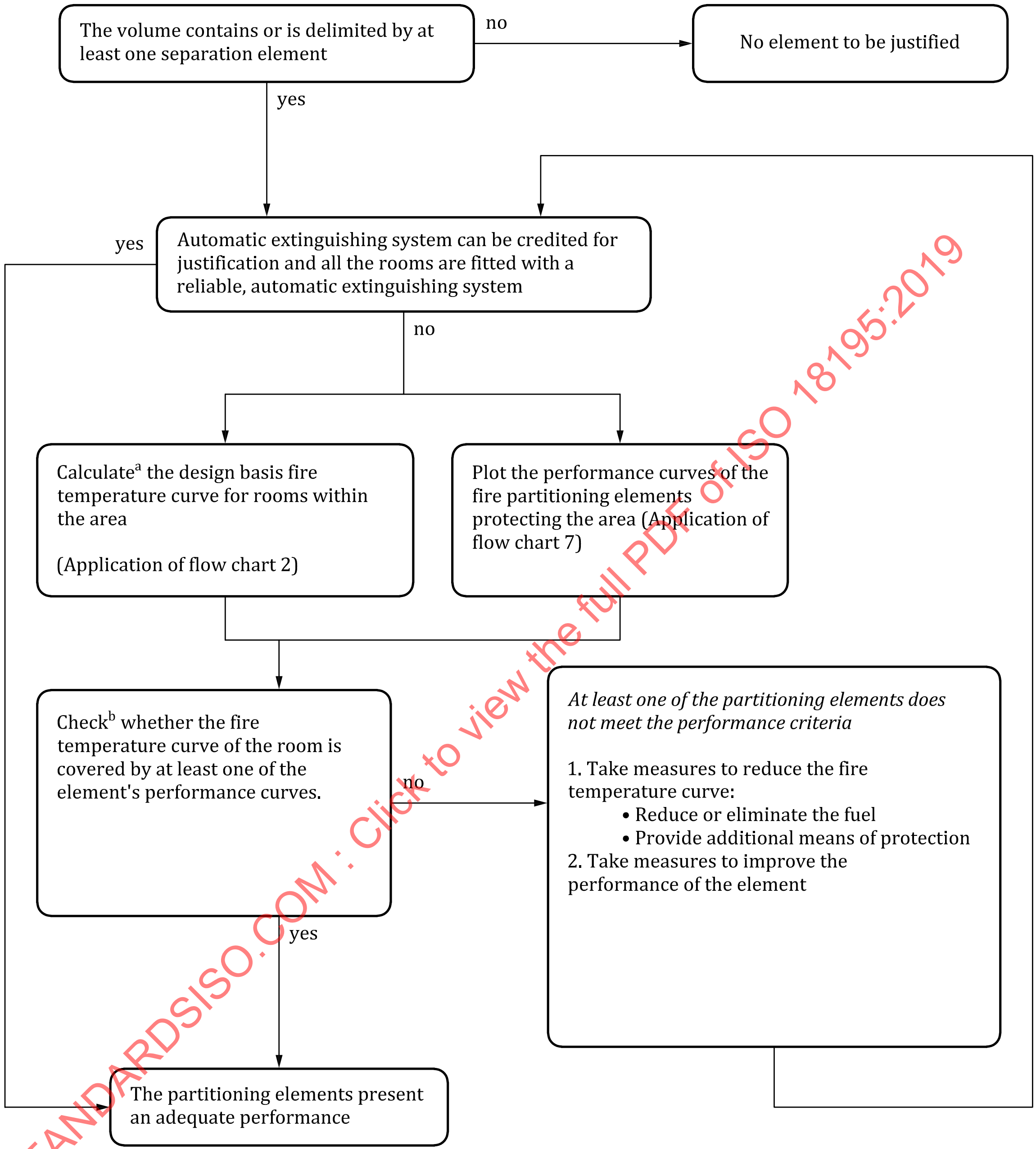
As previously said, the aim of the present method is to provide data to allow the verification of the adequate performance of the fire barriers, in order to design the fire partitioning of a NPP. Considering a separation between a room and another, the fire barriers will be correctly designed if a fire inside the one room does not affect or propagate to the second one. For each concerned fire barrier, this supposes that at least one performance curve from the performance curve diagram covers the design basis fire temperature curve of the room. In other cases a better performing fire barrier has to be found, or modifications adopted in the fire volume to reduce its design basis fire temperature curve profile.

4.4 Fire barriers and structural elements

The scope of the present method concerns the justification of partitions and partitioning elements as defined (see Clause 3). Nevertheless, structural element like walls, ceilings and floors may have their fire resistant rating obtained by calculation (e. g. Eurocodes 1 to 6[41][42][43][44][44][45][46][47] through ISO TS 24679) and not from tests. In those cases, the method described in Clause 6 can be prohibitively difficult to apply, due to the need for experimental tests. The scope of the method can be considered to exclude structural elements like concrete, whose performance may be verified by calculation, regardless of the time/temperature curve. Structural elements are generally over-rated regarding fire, especially concrete walls, floor, and ceilings in the nuclear island of NPP.

4.5 Overall flowchart (flowchart 1)

An overall flowchart is given in Figure 3.



a For each room or for each room not fitted with a reliable, automatic extinguishing system when those systems can be used for the justification of partitioning (see 5.4.1).

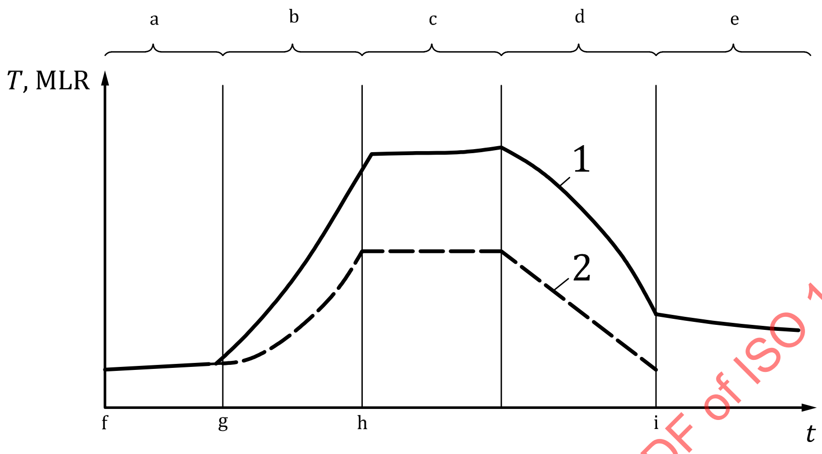
b For each partitioning element in each room or for each room not fitted with a reliable, automatic extinguishing system, when those systems can be credited for the justification of partitioning (see 5.4.1).

Figure 3 — Flowchart 1

5 Determination of the design basis fire temperature curve (room fire curve)

5.1 General considerations in room fire scenarios

The assessment of a fire scenario, from a design perspective, depends mainly on the characteristics of the room concerned and on the fire scenarios taken into account. The temperature profile of room fire can be assumed to follow the idealized curve similar to that shown in Figure 4.



Key

t	time in min
T, MLR	temperature in °C or mass loss rate in kg/s
1	room temperature
2	mass loss rate (pyrolysis rate)
a	Stage 1 ignition
b	Stage 2 growth
c	Stage 3 fully developed (Fully developed fire is generally limited by ventilation rate (oxygen inlet))
d	Stage 4 decay
e	Smoldering, end.
f	Ignitiator.
g	Ignition.
h	Flashover.
i	Fuel exhausted.

Figure 4 — Typical stages of a room fire

5.1.1 Typical development stages of a compartment fire

5.1.1.1 Phase 1: ignition

Exposed to a heat source (initiator of the fire) the material will heat up, mainly by conduction from the exposed surface. Beyond a critical surface temperature, thermal degradation of the material will create a gas phase by pyrolysis. The mixture of combustible pyrolyzed gases with air leads to the formation of a flammable gas phase. The ignition may occur under the effect of an additional source (flame, incandescent particle) or directly by chemical oxidation reactions (spontaneous ignition).

5.1.1.2 Phase 2: growth

The diffusion flame generated creates a thermal flux which contributes to its surface spread (start of the fire). The spreading rate of the flame depends on the chemical nature of the material, but is also greatly affected by physical and geometrical factors.

If the fire breaks out in a room, the temperature of this room rises gradually, even quite slowly in some cases, such as fire-resistant electric cables. At this step, the oxygen supply is sufficient to burn all the pyrolyzed gases. The fire is therefore said to be "fuel limited".

5.1.1.3 Phase 3: fully developed fire

The increase in ambient temperature induces a temperature rise and the pyrolysis of the various fuels present within the room, particularly those close to the ceiling. When a critical temperature is reached, flashover occurs, which consists of the simultaneous combustion of the majority of combustibles present.

In the event that flashover is not obtained, the fully developed fire would correspond to a stabilized rate of mass loss of the burning material (typical case for a pool fire, for instance)

At this stage, the fire may be limited by the oxygen supply to the room, in which case the fire is said to be "ventilation limited". This is frequently the case when flashover occurs.

5.1.1.4 Phase 4: decay

When most of the combustible material has been consumed (approximately 70 %[39]), the production of pyrolyzed gases becomes insufficient to maintain combustion, leading to the decay phase. This phase ends when all the credited combustibles have been consumed.

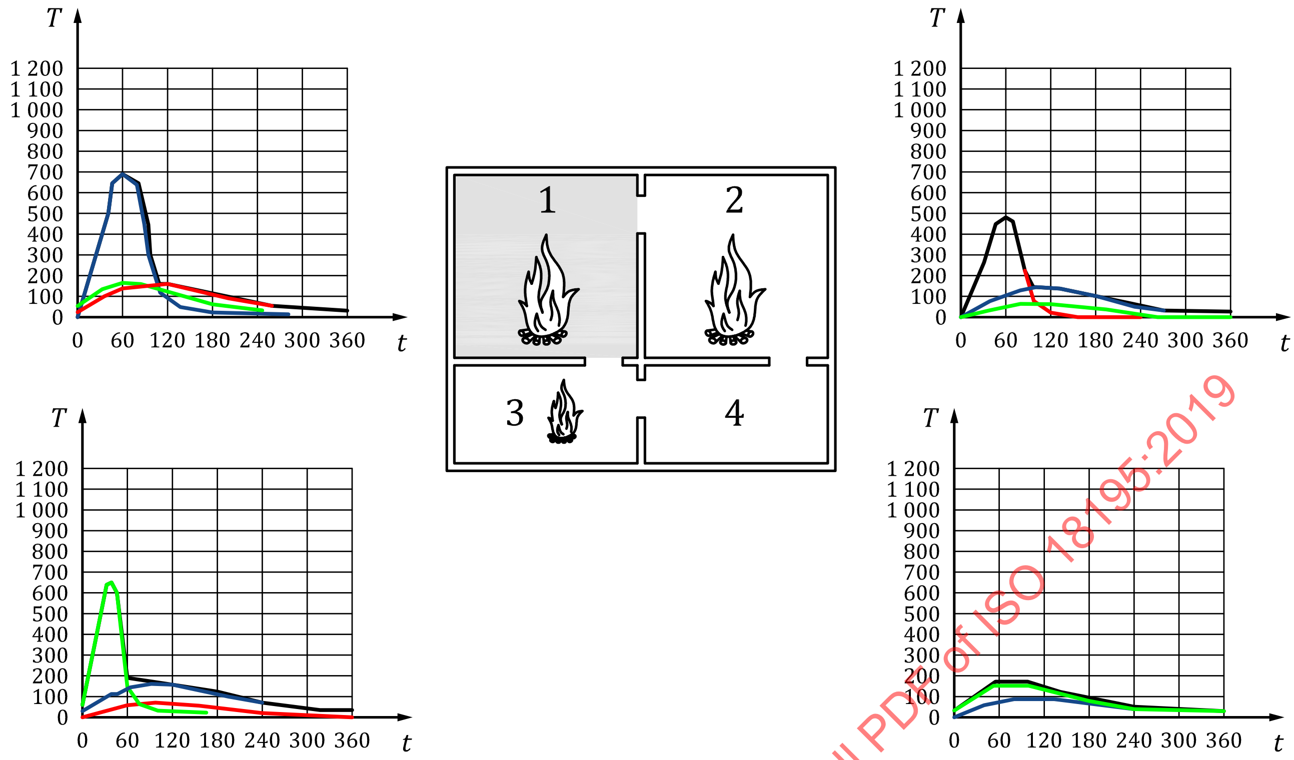
5.1.1.5 Phase 5: decay in the absence of combustion

The temperature of the room during this phase is only due to the thermal inertia of the walls and the room ventilation characteristics.

5.2 Defining the design basis fire temperature curve for a room

Inside any fire volume a fire scenario is calculated for each room. This calculation will give a fire temperature curve inside the room but also for the adjacent rooms (through openings). The overall design basis fire temperature curve assigned to a room is the curve that envelopes all of the different temperature curves obtained in the room, determined for each potential fire scenario in the fire volume. In this process, the possibility of spreading the fire from one room to another (i.e. ignition of the combustibles of the adjacent room) will be taken into account (see 5.4.5).

As an illustration, Figure 5 shows the temperature curves and design basis fire temperature curves in a volume posing four rooms in communication, coming from fire occurring in each room.



Key

t	time in min
T	temperature in °C
1	Room 1
2	Room 2
3	Room 3
4	Room 4 (no fire load)
blue line	Scenario 1 (fire in room 1)
green line	Scenario 3 (fire in room 2)
red line	Scenario 3 (fire in room 3)
black line	Temperature curve of the room

Figure 5 — Design basis fire temperature curve construction

5.3 Requirements concerning calculation tools

The software used for simulating fire scenarios shall provide an adequate level of quality and qualification. Relevant standards for the validation and verification, such as ISO 16730-1, or other methods approved by the authority having jurisdiction, shall be taken into consideration. The validation domain of the software is a fundamental issue; comparison to full-scale tests representative of the various NPP is necessary. Software identified in an international V&V benchmark (e.g. References [48] or [74], [75] and [76]) is highly recommended.

Apart from the validation of the software, proficiency with its use is required. This means a precise description of the input parameters and no ambiguity on their correct use in a specific situation, in accordance with the way they were used during the validation process (see also 5.5.3). As the present method is part of a nuclear safety demonstration, the nuclear authority will generally have to approve the choice of software and its correct use by the designer. The use of relevant guidelines like References [77] and [78] is highly recommended.

Three main categories of fire models are commonly encountered.

— Empirical correlation models: this category of models is based on pre-calculated curves or formulas (e.g. DSN 144[50], Compburn III[51], CDI[52], FDTs[53], FIVE-rev1 ([48]– vol 4), etc.). This category is characterised by quick and easy use, but poor flexibility and strong conservatism due to the need to cover a wide variety of situations.

— Zone models: These computer programs have been developed since the eighties (MAGIC[54][55][56], CFAST[57], COCOSYS[58], SYLVIA[58][59], etc.). They are generally based on a simplified one-dimensional calculation of the fluid behaviour, considering a homogeneous layer of smoke filled by the fire plumes and floating above a layer of fresher air. Gas circulation between rooms, heat exchange in the walls and target or ventilation systems, can then represented. This kind of fire model is more integrated than simplified fire models and gives a better estimate of the thermal conditions during the fire. They provide a mix between integrated fluid mechanics laws and experimental correlation which gives them a good global response, close to realistic conditions. They are limited in their ability to assess complex room geometry or thermal gradients.

— Computational Fluid Dynamics (CFD) fire models: This is the last generation of software used for fire prediction. Many of these computer programs appeared in the last fifteen years and remain the state of the art (FDS[61], JASMINE[62], OPEN FOAM[63], Code Saturne©[64], ISIS[65], etc.). There is a large discrepancy in the scope covered by each program, due to the fact that different approaches are employed for each. They are more dependent on the modelling choices made at the small scale for medium scale predictions and for that reason; some of them integrate real scale correlation correction factors (FDS). They provide more information on the local conditions but their qualification is more complex and their results are often considered more qualitative than quantitative. Of course, calculations are more onerous and take more time than zone or simplified fire models.

The present method has been developed for zone models, considering the fact that average values are necessary, and the number of simulations to perform may be significant. CFD code may also be used, but post-processing will be necessary to obtain applicable average values (see 7.1). In this process, principles given in Reference [61] (16.9.3 Layer Height and the Average Upper and Lower Layer Temperatures) are recommended. Algebraic model are not taken into account due to the fact that they would generally give overly conservative results and hardly deal with multi-room configurations.

Fire modelling is still an area of active research due to the inherent difficulties of the topic:

— Interaction between fluid mechanics, combustion including species and soot production, heat exchanges, pressure effects, etc.;

— Complex boundary conditions: structural components, ventilation, protection systems, extinction, etc.;

— Multiplicity of influent parameters, complexity of the configurations, complexity of fuel behaviours;

— Large scale and dynamic simulation, multiplicity of possible scenarios.

One of the main issues of a fire simulation is the hypothesis made on the mass loss rate of the combustible. In most cases, models cannot predict this quantity with sufficient accuracy, so fixed experimental full-scale data shall be used.

5.4 Assumptions and input data for numerical calculations

5.4.1 Fixed automatic fire fighting system (credited or not)

Fixed automatic fire fighting system may or may not be used to justify the partitioning efficiency. This depends on the authority having jurisdiction, and various standards (e.g. References [66], [67] and [68]) have different requirements on that issue. For that reason, the present methodology deals with both possibilities.

In cases where the activation of a reliable automatic extinguishing system is assumed, the fire partitioning elements of the room will be considered sufficient (no calculation required). In those cases, the extinguishment system will be identified as important for nuclear safety (reinforced reliability, maintenance and quality policy). Consideration will be taken of the maximum delay of starting of the system to determine the minimal resistance rating of the fire barriers.

5.4.2 Modeling assumptions

Modelling assumptions concern hypotheses or approximations regarding the physical phenomena inherent to the model. They strongly depend on the nature of the fire model and its validation file.

Modelling assumptions shall be in accordance with those chosen during the validation process in similar situations, and shall guarantee a conservative prediction for the relevant parameters. If specific values are necessary for specific configurations, they shall have been clearly identified in the software documentation and the validation process and shall be clearly documented in the engineer's report.

For zone models, all of the oxygen in the fire volume can be assumed to contribute to combustion. Even if this value is upper bound since it is accepted that from a concentration of oxygen in the air of less than 10 %, the fire source loses its power and tend to go out, this assumption covers the risk of fire located closed to an opening or ventilation generally not taken into account by zone models.

Regardless of the specific model, it shall correctly represent the oxygen depletion and take it into account in the heat release rate calculation (see 5.4.5).

In general, combustion efficiency is assumed to be 100 % for zone models and CFD models with the exception of specific cases which have been validated for this parameter.

5.4.3 Characteristics of a room

5.4.3.1 Room shape:

A room is characterised by the following:

— its internal dimensions;

— the thermal properties of the walls and their thicknesses;

— the dimensions of the openings communicating with adjacent rooms.

For simplified or zone models, the room can be represented by a rectangular volume with three dimensions:

a) Length (m);

b) Width (depth) (m);

c) Height (m).

For non-rectangular rooms, the dimensions (length and width) should be as close as possible to dimensions defined in the civil engineering drawings whilst conserving the floor area of the room.

For fire model less limited in geometry (e.g. CFD), it will be preferable to take into account the real shape of the room.

When the room concerned communicates with another with no separation wall these two rooms should be combined to form an equivalent room.

5.4.3.2 Openings at the boundaries of the room (Non fire resistant elements + shafts)

All openings at the boundaries of the room should be taken into account for the calculation. The term “opening” refers to all open shafts and elements (doors, penetrations, etc.) not resistant to fire at the boundaries of the room concerned.

The minimum data needed to specify an opening are:

a) Width (m);

b) Height (m);

c) Sill[1)] (m).

Name of the opposite room

5.4.3.3 Nature and thickness of the walls

The thermal characteristics and thickness of the walls and floor have to be known.

For the concrete wall and floor (the most common material in a plant) thermal properties taken into consideration are those of the design or, in case of lack of information, those of typical nuclear concrete characteristics. For example, typical characteristics might look like:

a) Density: 2 300 $kg \cdot m^{-3}$;

b) Heat capacity: 1 100 $J \cdot kg^{-1} \cdot K^{-1}$;

c) Thermal conductivity: 1,40 $W \cdot m^{-1} \cdot K^{-1}$.

Since the coefficients of conductivity and heat capacity of normal concrete vary with temperature, the values taken into consideration are those taken at 350 °C. No credit of the water present in the concrete was taken.

When possible, the thermal characteristics of the concrete as a function of temperature are used.

5.4.3.4 Mechanical ventilation

Mechanical ventilation systems are not taken into account if it can be reasonably assumed that the dampers will close during the early stages of a fire. Activation is generally based on detection and also provided for by the presence of a fuse link placed in the direction of the flow for dampers in extraction mode and a remote fuse for dampers in blowing mode. This principle of installation is used to ensure the closing of dampers during the growth phase (See 5.1).

In other cases, the ventilation system can be assumed to maintain its nominal levels, unless a validated model of the ventilation network is provided by the fire model.

5.4.3.5 Air leakage

Air leakage rate or law, when known, shall be specified. Introducing leakage (e. g. small equivalent opening) generally facilitate the numerical calculation by limiting the pressure rise.

5.4.4 Nature of fuels

The fuels likely to be present in the rooms of nuclear buildings may be classified according to their nature:

Liquid fuels (hydrocarbon fuels, with fast dynamics):

— Fuel, oil, solvents, etc.

1) Distance between the lower part of the opening and the floor of the room concerned.

<u>Electromechanical equipment:</u>

— Cubicle;

— Console;

— Cabinet;

— Transformer;

— Rectifier;

— Inverter;

— Circuit-breaker cell;

— Motor;

— Battery;

— Personal computers;

— etc.

<u>Electrical cables:</u>

— Thermoset or thermoplastic cables;

— Control or power cable.

<u>Other materials:</u>

— Paper;

— Cotton (textile);

— etc.

A method for determining the heat release rate associated with these different kinds of combustibles is proposed in the next clause.

5.4.5 Fire scenarios

5.4.5.1 Summary

A fire scenario starts with the ignition of an initial fire source (primary fire source), which may spread to the other fuels in the room (secondary fire sources), then possibly to fire sources in adjacent rooms.

4 types of initial fire sources have to be considered:

a) fire of liquid fuel with fast dynamics;

b) electromechanical equipment fire;

c) cable fire;

d) fire of other materials.

The fire spreads by the ignition of secondary fire sources. Some fire models (for instance MAGIC) can simulate these secondary fire sources, but this requires details on the configuration of the rooms and a precise distribution of combustible mass. This is not universally possible across the spectrum of fire models. Therefore, a single and unique fire source per room is considered and two scenarios applied: a scenario with and without spread of the fire for each regular fire volume.

5.4.5.2 Fire spreading

When a fire ignites at a given location, it can either remain localised to the first fire source or propagate to other fire sources. If the propagation becomes significant, most of the combustible mass within the room may become involved. Different strategies are therefore necessary to model a fire which stays localised (one fire source burning) or a fire which propagates (all fire sources burning). In order to facilitate the assessment of the fire temperature curve, a selection criterion is provided by this method. The determination of modelling strategy can be predetermined based on the fire source configuration. This approach supposes that a certain number of conditions are met and, for localised fires, the no-spreading hypothesis has to be confirmed by calculation through the temperature obtained. These aspects are detailed in the following sections.

5.4.5.3 Spreading criteria: PFG/PFL

The choice of scenario and, in particular, the risk of spread shall be determined by the installation configuration and concentration of combustible masses in the room. A scenario may be classified by its spreading criteria as either PFG or PFL.

The PFG criterion "Possibility of Fire getting Generalized" represents a large combustible mass concentrated in the room which may generate flashover (probable spread of the fire).

The PFL criterion "all Possible Fires remaining Localised" represents a significant combustible mass concentrated in the room which may generate a localised fire (spread unlikely to happen).

Rooms where “neither PFG nor PFL” criteria are reached are said to be “neither PFG nor PFL”. The concentration of combustible masses in such rooms is not enough to generate a widespread fire (and there is no necessity for further verification).

Examples for PFG and PFL Criteria are proposed in Annex A.

In a PFG room, the hypothesis of a spreading fire will be systematically applied, considering that it is likely to occur.

In a PFL room, the hypothesis of a localized fire source will be initially applied. If no propagation criteria are reached, the room will be confirmed as a PFL room, otherwise it will become a PFG room.

In a “neither PFL nor PFG” room the PFL approach will be applied in the scenarios. A low heat load threshold (LHLT) is introduced (see Figure 8) to avoid calculations in the case of rooms that are neither PFL nor PFG and don’t present a significant quantity of combustible material. A value of $\left(960 \cdot \sqrt{A_T}\right)$ MJ (where A_T is the total internal surface area of the walls) is recommended for LHLT when there is no fire partitioning component with a fire resistance rating less than 1 h[39].

NOTE This value correspond to one hour of combustible, following the standard temperature/time curve with the MQH correlation[79].

5.4.5.4 Scenarios taking into account the spreading factors

The choice of scenario is therefore based on 2 parameters: the nature of the initial fire source and the presence of a PFG or PFL criterion in the room. Flowchart 3 uses these parameters to define a scenario from the following list.

List of different fire scenarios likely to be encountered in a NPP, classified according to type and initial fire source

<u>Rapidly growing hydrocarbon liquid fire:</u>

— Scenario 1: liquid fire (PFG)

— Scenario 2: liquid fire (PFL)

Electromechanical equipment fire:

— Scenario 3: electric equipment fire (PFG)

— Scenario 4: cabinet fire (PFL)

— Scenario 5: cubicle fire (PFL)

Cable fire:

— Scenario 6: cable fire (PFG)

— Scenario 7: cable fire (PFL)

Fire of other materials:

— Scenario 8: fire of combustible materials in storage (PFG)

— Scenario 9: fire of combustible materials in storage (PFL)

Scenarios 1, 3, 6 and 8 characterise flashovers (PFG). These scenarios include the spread of the initial fire towards the secondary fire sources of the room. All the combustible mass in the room is therefore likely to participate to the fire.

Scenarios 2, 4, 5, 7 and 9 characterise localised fires (PFL), only the primary fire source contributes to the fire without spreading towards the secondary fire sources of the room. However, if the results of the calculation result in a temperature of more than spread temperature threshold (STT) in the hot layer, the fire may spread to all the combustible masses in the room. A recommended value for the STT is 350 °C (value based on[70]). Values of more than 350 °C may be considered acceptable by the Authority having jurisdiction. In cases where STT is reached, the scenario shall be reconsidered according to Table 1 below.

Table 1 — Fire Scenarios

Initial scenario	Scenario to be taken into consideration if the temperature of the room reaches STT
2	1
4	3
5	3
7	6
9	8

The spread of the fire towards the secondary fire sources of the adjacent rooms shall be taken into account if the temperature of the adjacent room exceeds STT. This supposes that the plant has strict controls to limit the presence of flammable materials.

5.4.5.5 Credited combustible mass

The credited combustible is the combustible material likely to be affected by the generic effects of a fire (radiation, convection, conduction) and which may come into contact with oxygen.

This includes at least the combustible mass of the primary fire source and may include all the combustible mass in the room if the initial fire spreads.

The quantity of air available to supply the fire with oxygen is:

— the quantity of air in the volume of the fire compartment if the room concerned belongs to a fire compartment;

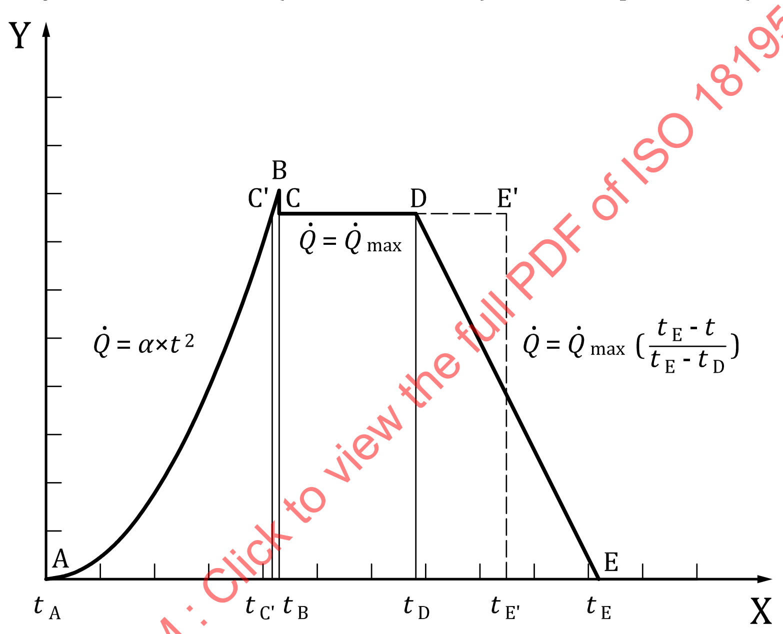
— the quantity of air in the volume of all interconnected fire cells if the room concerned belongs to a fire cell.

The credited combustible mass of the primary source in a PFL room is the initial combustible mass of the PFL fire source plus the credited combustible mass likely to be present in the plume from the fire source.

WARNING — Considerations on localised fire suppose that no other significant fire source is likely to be ignited by the initial fire source. Secondary sources in the plume, in the ceiling jet or at a limited distance from the first source should be taken into account (recommended value: 4 m or a benchmark established by the Authority Having Jurisdiction). If those cases, a PFG criteria shall be adopted.

5.4.5.6 Pyrolysis rate curves

A scenario is mainly characterised by its rate of pyrolysis (mass loss rate) $\dot{m}$ (kg·s^{-1}). It starts with a spreading phase followed by a steady state and finally--for solid fuels--a decay phase. Figure 6 below shows the rates of pyrolysis for solid fires (scenarios 3 to 9) and for liquid fires (scenarios 1 and 2).



Key

X time, t, in s

Y mass loss rate, in kg/s or HRR, in kW

Figure 6 — Pyrolysis rate or Heat release rate curve

There are three main stages:

a) spreading stage [AB];

b) fully developed fire [CD] or [CE'];

c) decay stage [DE].

<u>Spreading phase [AB]:</u>

Combustion is controlled by the fuel. Heat release rate increases gradually following Formula (2): until it reaches a maximum $\dot{Q}_{max}$:

$$\dot{Q} = \dot{m} \times \Delta H_C = a \times t^2 \quad (2)$$

where

$\dot{Q}$ is the Heat Release Rate (kW);

$\dot{m}$ is the rate of pyrolysis ($kg \cdot s^{-1}$);

t is the time (s);

α is the growth factor ($kJ \cdot s^{-3}$);

ΔH_C is the net heat of combustion of the fuel ($kJ \cdot kg^{-1}$);

$\dot{Q}_{max}$ is the maximum heat release rate of the fire source.

Fully developed fire [CD] or [CE']:

The power of the fire may be limited by the supply of air to the openings. In this case, combustion is controlled by the ventilation. In the other case, combustion is controlled by the fuel mass loss rate. During this phase, the power of the fire remains constant up to the consumption of either:

— 70 % of the credited combustible mass for solid fuels (segment [CD]), or

— 100 % of the credited combustible mass for liquid fuels (segment [CE']).

The value of 70 % is assumed for cellulose type fires. This value is also used for cable fires, since it is more conservative than the values measured during large scale testing (approximately 55 % for cable fires[68]).

Decay phase [DE] (for solid fuels):

Pyrolysis eventually becomes insufficient to maintain ventilation-limited combustion. The rate of pyrolysis decreases linearly until 100 % of the credited combustible mass is consumed. This decay is calculated on the assumption that the time required to consume the remaining 30 % of mass is twice that of the time required to burn the equivalent mass at the maximum rate of pyrolysis.

Triangle [C'BC]:

Triangle C'BC occurs when the "fully developed fire [CD]" is limited by ventilation. In this case, the need for air is greater than the ventilation flow rate (point C'), and the fire consumes the air in the room. When the air is consumed (point B), the power of the fire adjusts to what the ventilation flow rate will allow (point C).

In the case of a fuel-limited fire, the points B, C' and C are combined.

Definition of time sequence from ignition to consumption of all credited combustible mass:

When the fire is controlled by ventilation:

— t_A: ignition of the fire source;

— $t_{C'}$: time to reach ventilation rate;

— $t_B - t_{C'}$: time to consume the air in the room ($t_B = t_C$);

— t_D: time to consume 70 % of the combustible mass (solid fire);

— $t_{E'}$: time to consume 100 % of the mass following $\dot{Q}_{max}$;

— t_E: time to consume 100 % of the fuel with decay phase (solid fire): $t_E - t_D = 2 \cdot (t_{E'} - t_D)$.

When the fire is controlled by the fuel:

— t_A: ignition of the fire source;

— $t_B = t_C = t_{C''}$: time to reach maximum heat release rate;

— t_D: time to consume 70 % of the combustible mass (solid fire);

— $t_{E''}$: time to consume 100 % of the mass at maximum power (liquid fire);

— t_E: time to consume 100 % of the fuel with decay phase (solid fire): $t_E - t_D = 2 \cdot (t_{E'} - t_D)$.

5.4.6 Recommended value for pyrolysis rates

The building of pyrolysis rate curves is a key point in the building of fire code. The description of the different parameters of the curve (growth factor, maximum pyrolysis rate) may come from user experience and best practices. Recommended values are provided in Annex B.

5.5 Design basis fire temperature curve calculation process

5.5.1 Data input

The input data required to plot the design basis fire temperature curve according to ISO 834-1:1999, Figure 7, of the rooms of a fire volume is as follows:

— dimensions of the rooms;

— thickness and thermal characteristics of the walls;

— dimensions and location of the openings;

— nature of the fuels;

— presence of an automatic extinguishing system;

— presence of PFG and/or PFL criteria.

The point of fire origin shall be positioned in the centre of the room.

5.5.2 Modelling of the fire volume and scenarios

The modelling process is carried out in three steps as described in flowchart 2 (see Figure 7). An iterative process is handled when there are adjacent rooms in communication inside the volume.

A fire temperature curve is defined for each room, considering the fire sources inside the concerned room. The contribution of the concerned room to the other rooms is also calculated. At the end of the process, all the contributions are taken into account for a given room.

When the STT is obtained for a fire temperature curve, fire propagation has to be assumed in the concerned room, which means that a PFG hypothesis is taken.

5.5.3 Modelling options

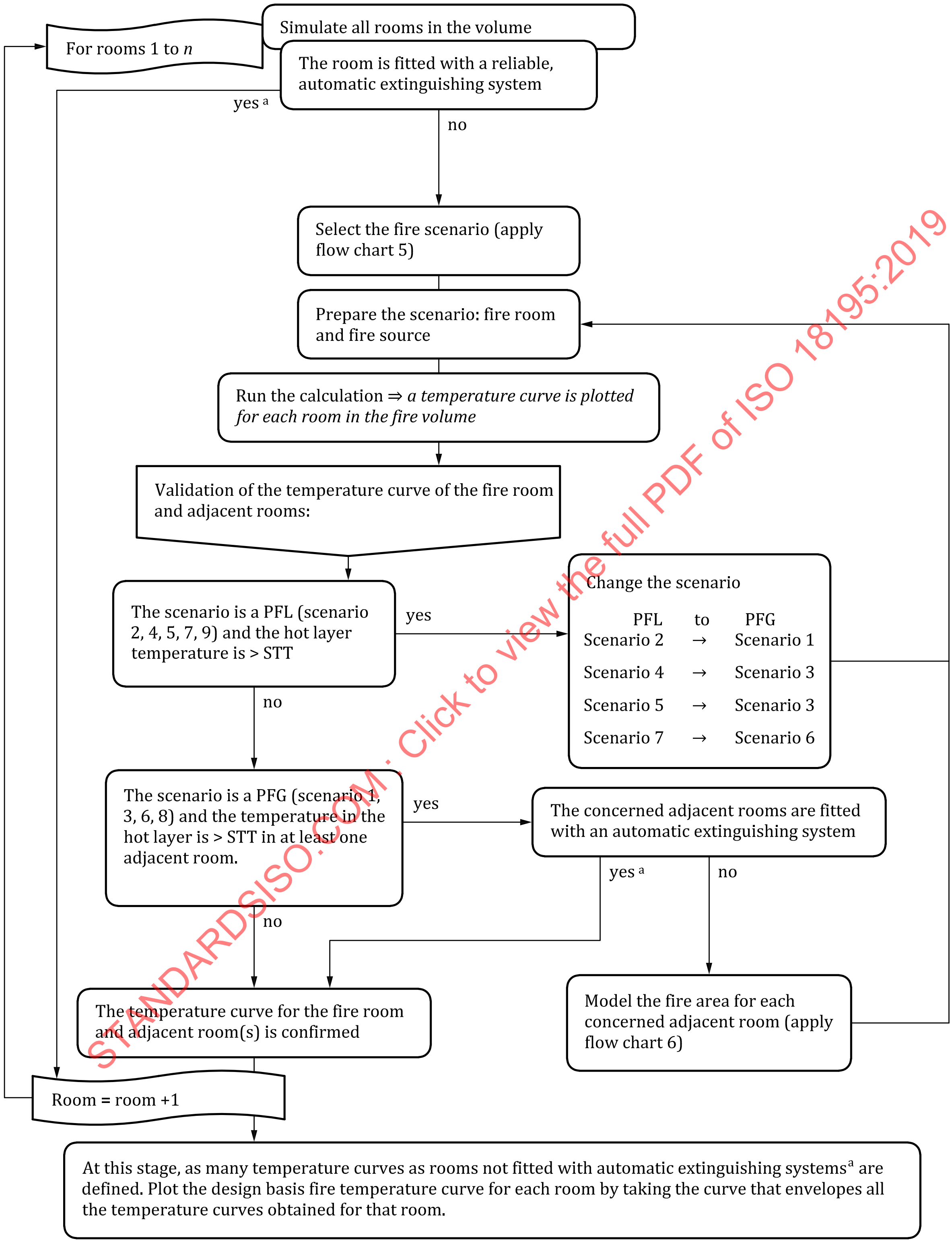
Modelling options depend on the software used. As an overall requirement, options shall be consistent with those used in the validation file of the software. Where there is some degree of flexibility with certain parameters, conservative options shall be used preferentially.

Attention will be paid to typical influent parameters like combustion efficiency, Low Oxygen Indice, or management of unburned gas for example. Conservative assumption shall be preferably assumed on these parameters.

Considering that most of the existing numerical fire models will use the fuel mass loss rate as an input, the production of unburned gas and subsequent burning in adjacent rooms may be proposed as an option. In that case, it is preferable to limit the production of unburned gas when studying the initial room, and favour it when studying the adjacent room.

5.6 Determination of the fire temperature curve

Figure 7 (flowchart 2) describes calculation of the fire temperature curve using zone or CFD fire model.



a Applies only when active system credit is accepted (see 5.4.1).

Figure 7 — Flowchart 2: calculation of the fire temperature curve using zone or CFD fire model

Figure 8 (flowchart 3) describes the selection of the initial fire scenario.

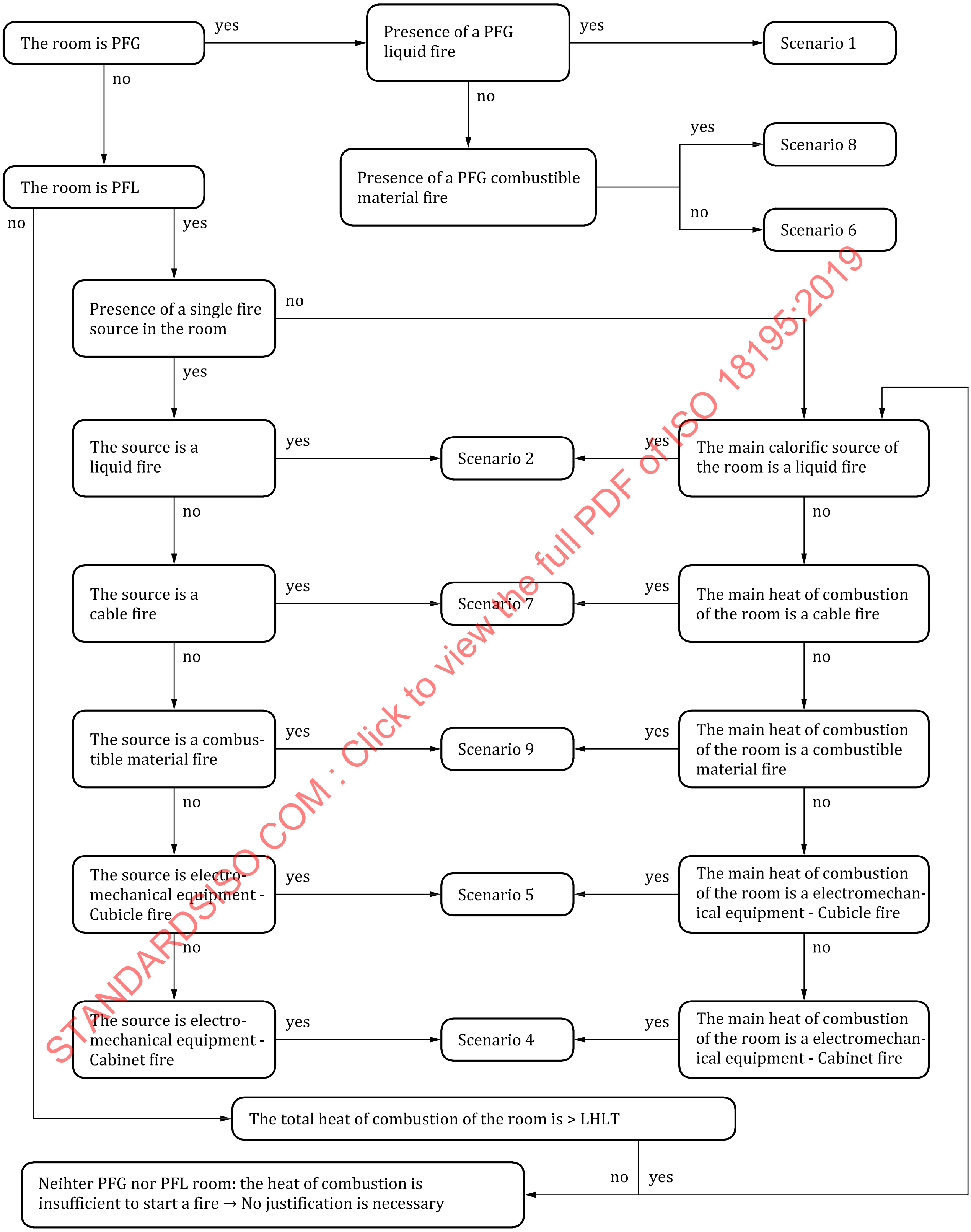


Figure 8 — Flowchart 3: selection of an initial fire scenario

Figure 9 (flowchart 4) describes the selection of the secondary fire scenario.

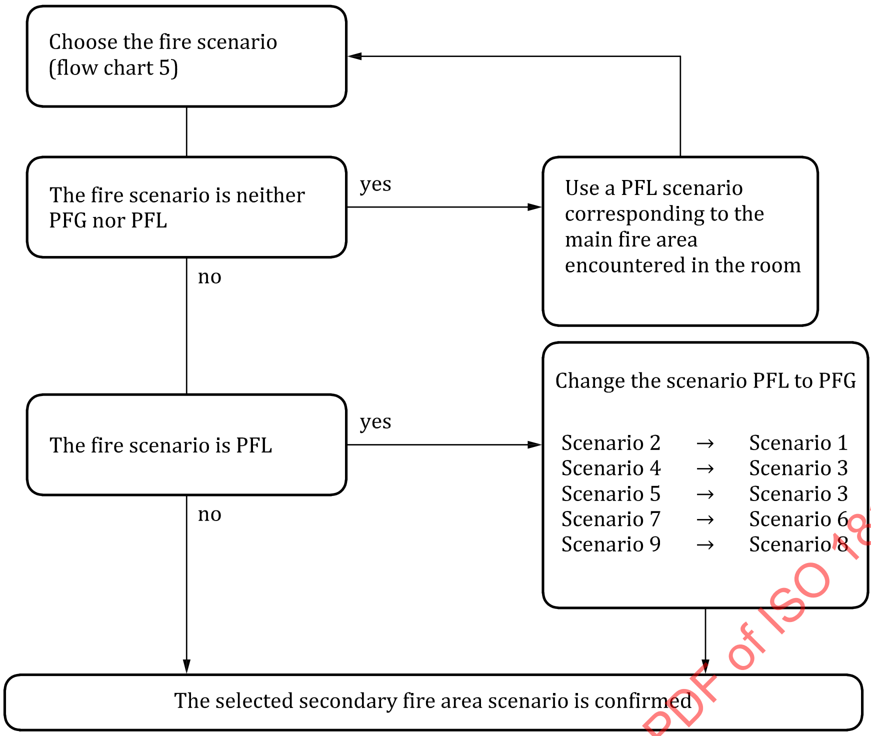


Figure 9 — Flowchart 4: selection of a secondary source scenario

6 Determination of the performance of fire barriers (performance curve diagram)

6.1 Principles

The performance curve of a partitioning element is a temperature/time curve for which the fire resistance criteria threshold values are not reached. The partitioning elements considered are fire resistant products: doors, dampers, shutters, housings, cable racks, wrapping, etc.

6.2 Characterization of the performance diagram: global methodology

The fire resistance performance of a fire barrier is characterised by one or several temperature/time curves.

The process to establish those curves is broken down into two main phases:

— Phase 1: Mainly qualitative, consists of a global analysis of the standard tests and the determination of the main reasons for reaching the limiting rating criterion;

— Phase 2: Quantitative (by modelling) and/or experimental, provides the performance curves of the products.

The methodology used according to the type of product adopted is described in Figure 10 (flowchart 5) given below.

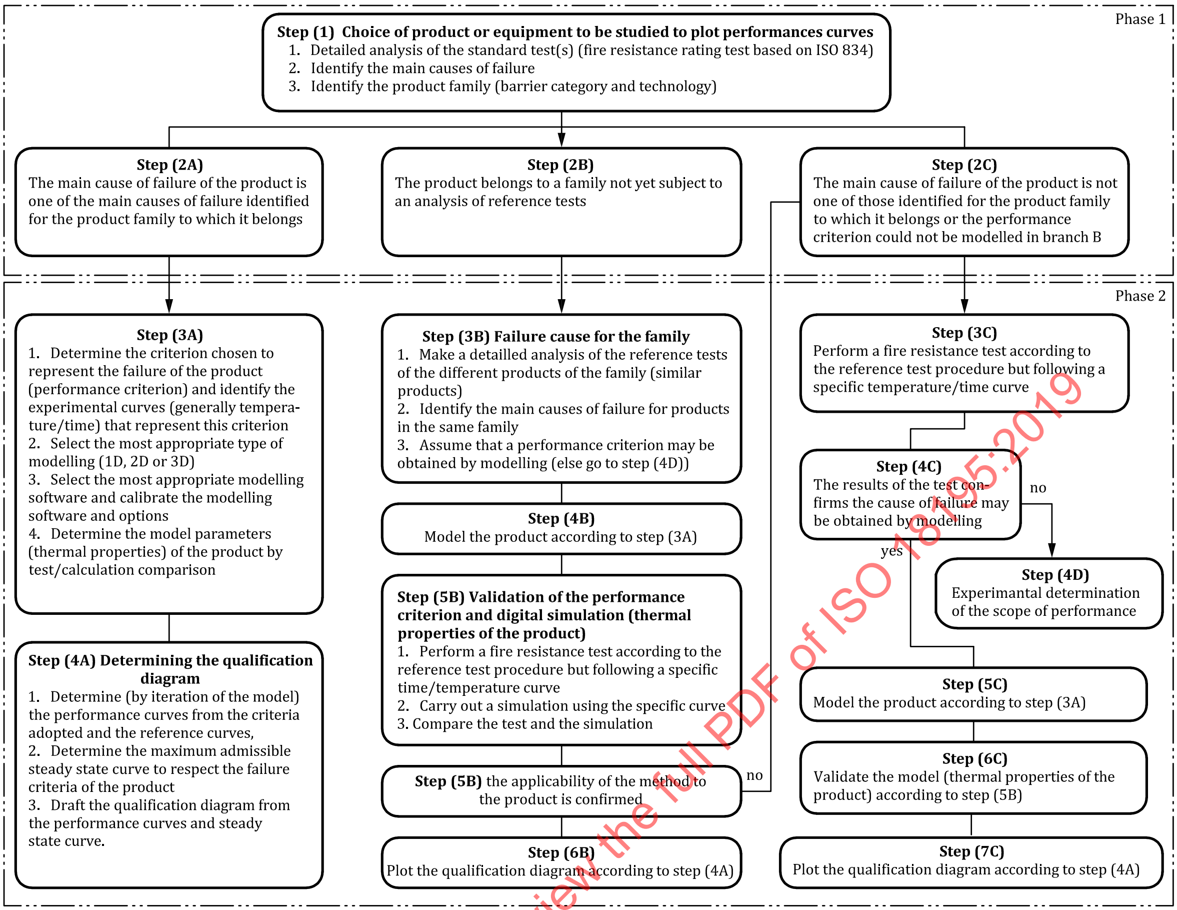


Figure 10 — Flowchart 5: Global methodology

6.3 Phase 1: analysis of the standard test

Phase 1, which is broken down into 2 steps, consists of a detailed analysis of the standard test of the product. The aim is to determine the limiting performance criterion of the product's fire rating (step 1) and to classify the product in a branch A, B or C, each of which corresponds to a different study approach (step 2).

Step 1 is carried out with reference to the test report paying particular attention to the following:

— the standard test method used;

— the observations made during the tests;

— the measurements taken mainly in terms of temperatures in time;

— the limiting performance criterion reached during the standard tests;

— the physical phenomena that led to reaching the limiting criterion and the corresponding rating.

This step aims to identify the nature and the value of the main criterion resulting in the failure of the product providing its time rating (for example: thermal insulation (nature) – ΔT_{local} > 180 °C on the surface not exposed to the fire (criterion value)).

Step 2 consists in checking whether the performance criterion is appropriate for products belonging to the same “family”. A family means products of same category and similar technology, grouped for their similar behaviour (see examples in Annex C). There are 3 possibilities (called “branches”):

— branch A: The product belongs to a family already studied and the main cause of its loss of classification is similar to the one adopted for the family.

— branch B: The product does not belong to any product family already identified.

— branch C: The product belongs to an existing product family but the main cause of its loss of rating is not similar to the one adopted for the family.

Step 1 has already been carried out on different products or ranges of products for the following families:

— doors;

— dampers;

— smoke control ducts;

— ventilation ducts;

— housings;

— cable rack enclosures;

— penetration seals.

An example of these analyses is set out in Annex D (cable wrap).

6.4 Phase 2 branch A: determination by calculation

The purpose of this phase is to determine the performance curves and work out the performance diagram for the product.

6.4.1 Study approach

The study approach for products classified in branch A is broken down into 2 steps (3A and 4A).

— Step 3A is intended to retrieve the results of the standard test numerically. Steps are:

1) To establish the limiting performance criterion and identify the standard curves (generally temperature-time) representative of the performance criterion and required for comparison with the calculations;

2) To select an appropriate type of modelling (1D, 2D or 3D);

3) To select appropriate modelling software;

4) To determine the thermal properties of the material by test/calculation comparison.

— Step 4A is used to determine the performance curves and deduce the performance diagram.

1) To iteratively determine the performance curves through fire modelling using the established thermal properties.

2) To determine the maximum steady state curve that will not reach the failure criteria of the product.

3) To produce the performance diagram from the performance curves and steady state curve.

6.4.2 Selection of representative experimental curves

In the previous stage, the failure criterion of the product was identified (step 1). The next step is to recreate it through numerical simulation. Therefore, one shall identify the experimental curves (generally time/temperature) that can be used for the purpose of determination of thermal properties and comparison between the results of the standard test and numerical simulation

The curves to select are those in accordance with the identified failure criteria, but also all complementary curves obtained in locations other than the criterion measurement (within the thickness of the product, for instance) that can be used to validate the properties of the materials or the intermediate conditions to analyse the physical behaviour of the materials.

For temperature, these curves mainly consist of the intermediate temperature curves available. For example, the temperature measured at intermediate thicknesses (at mid-thickness or at the interface of different materials).

The average and envelope temperature curves obtained during the experimental test(s) will be adopted. Barrier performance data that was not used for fire rating purposes, but that may contain useful data should be considered. In general, a curve being very different to those used to reach the criterion should not be adopted. On the other hand, if 2 curves are different from the others but have a similar appearance one should consider the possibility of a local failure (seal, leak, equipment, etc.). One shall identify the shape of the curves providing information on the properties of the materials, such as plateaus or inflexion points.

6.4.3 Calculation tools and choice of the modelling

The analysis of the tests, specifically the nature of the failure criterion, leads to a certain type of calculation mode, and tools. The failure criterion is generally thermal since the fire resistance criterion characterises thermal insulation of the product. A thermal transfer model is used in all cases, assuming that temperature is characterizing the product physical state and behaviour.

The choice of the numerical model may also lead to defining a different performance criterion but which encompasses the one identified during step 1. For example, when the performance criterion is at ΔT_{local} > 180 °C on the surface not exposed to the fire, the choice of a one-dimensional model would lead to adopting a performance criterion of $\Delta T_{average}$ = 140 °C.

The tool is 1D, 2D or 3D, depending on the nature of thermal exchange—one, two, or three dimensional.

As for fire (see 5.3), the computer programs used for this analysis will be duly validated by comparison to representative experiment. Hypothesis and modelling options shall be justified.

Models will preferably take the following into account:

Thermal dependence of material properties — Radiation and convection boundary conditions

On the exposed face, the boundary conditions are defined by the furnace control system used during the tests (thermocouples as previously used in Europe, plate thermocouples currently used, furnace control heat flux system required by Underwriters Laboratories, etc.).

For example, by convention on the current European furnace control system (plate thermocouples), when no more advanced modelling is available, it can be considered that on the surface exposed to the fire:

In the absence of more specific information, certain assumptions can be made about the exposed face. For example, regarding the plate thermocouples used in European furnace control systems:

The plate emissivity is expressed by:

$$\varepsilon = \varepsilon_{material} \times \varepsilon_{furnace}$$

where

$\varepsilon_{furnace}$ = 1;

$\varepsilon_{material}$ = 0,7.

The coefficient of convection is 25 W/m^{2}K.

On the unexposed surface of the product the boundary conditions may be:

— an open environment (e.g. door). In that case exchanges will be defined by the following coefficients of convection:

  — 9 W·m^{-2}·K^{-1}. if losses by radiation are included;

  — 4 W·m^{-2}·K^{-1} if losses by radiation are calculated separately.

— a closed environment (e.g. casing). In that case it can be easier to model the air included in the product. Adiabatic conditions maybe also used, when it can be shown that the temperature of the ambient environment remains very close to the temperature on the unexposed surface.

Furthermore, material density can be considered constant.

6.4.4 Thermal properties of materials

6.4.4.1 Principles for the determination of thermal properties

The properties of materials are obtained by comparing the calculations with the experimental curve(s) plotted in 6.4.2.

Thermal properties obtained are satisfactory when:

— T_{cor}, the correlated temperature gap between the calculated temperature ($T_{num,i}$) and the experimental temperature(s) ($T_{exp,i}$) (average or maximum value) is less than 10 % (or as approved by authority having jurisdiction) of the value of the performance criterion adopted (the shape of the curve is respected)

— the time to reach of the calculated criterion adopted is +/- 10 % (or as approved by authority having jurisdiction) of the experimental time

The correlation temperature gap is calculated according to equation (3):

$$T_{cor} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_{exp,i} - T_{num,i}\right)^2} \qquad (3)$$

where

n is the number of experimental points;

i is a given experimental/calculated point.

This iterative task may be difficult and time consuming. Therefore, certain simplifying assumptions can be made as follows in 6.4.4.2 and 6.4.4.3.

6.4.4.2 Known materials

Certain material properties are already known and standardised; it would be wise to start the process from the properties mentioned in the standards.

In particular, for construction materials:

— steel: thermal properties according to temperature given in [44] may be adopted;

— concrete: thermal properties according to temperature given in [43] may be adopted.

When common materials (for example, copper for the behaviour of electric cables conductor) are included in the test, their properties may come from literature.

Nevertheless, it is acceptable to modify those properties in the process of determining the adequate model (see 6.4.4.3) in order to obtain a reliable representation of the global product behaviour.

6.4.4.3 Materials with properties to be determined

For the materials inherent to the product studied and for which the simulation of the standard test is used to determine the properties, it is necessary to simplify changes in properties according to temperature.

The properties of materials are represented mainly by the following:

— specific heat dependent upon temperature ($J \cdot kg^{-1} \cdot K^{-1}$);

— thermal conductivity dependent upon temperature ($W \cdot m^{-1} \cdot K^{-1}$).

Specific heat:

The effects of vaporization (generally water) can be represented by an increase in material specific heat.

In general, the specific heat of materials is a value between 800 and 1 500 $J \cdot kg^{-1} \cdot K^{-1}$ at ambient temperature.

Certain physical phenomena can be represented more simplistically by a change in specific heat:

— a temperature plateau (generally associated to a change of phase): local increase in specific heat close to the temperature of the plateau (this increase may occur in high ratios, from 2 to 20 in relation to specific heat at 20 °C);

— a change of phase of the material which could slowly take in the effects of vaporisation: increase in specific heat over wide temperature ranges. In general, this change in specific heat starts at a decomposition temperature of the material which, in this case, remains constant up to the highest temperatures.

Conductivity:

— In so far as conductivity is concerned, it should be noted that in general, conductivity at high temperatures is different to that at normal conditions.

The conductivity adopted shall also take into account phenomena independent of the material itself, such as cracking, decomposition, bending, erosion by convection, bursting, or loss of adhesion between layers. It is therefore possible that the thermal analysis yields different thermal properties for the same material used in two different products.

The transfer of heat by mass transfer has to be taken into account in the conduction term, because it is not possible to model the migration of water. Conductivity is therefore often greater at temperatures below the boiling point.

It is therefore difficult to take thermal properties given in the literature into consideration. This is why comparison with temperature measurements others than the ones used for the failure criterion (intermediate temperatures) may enable one to refine thermal properties of the materials.

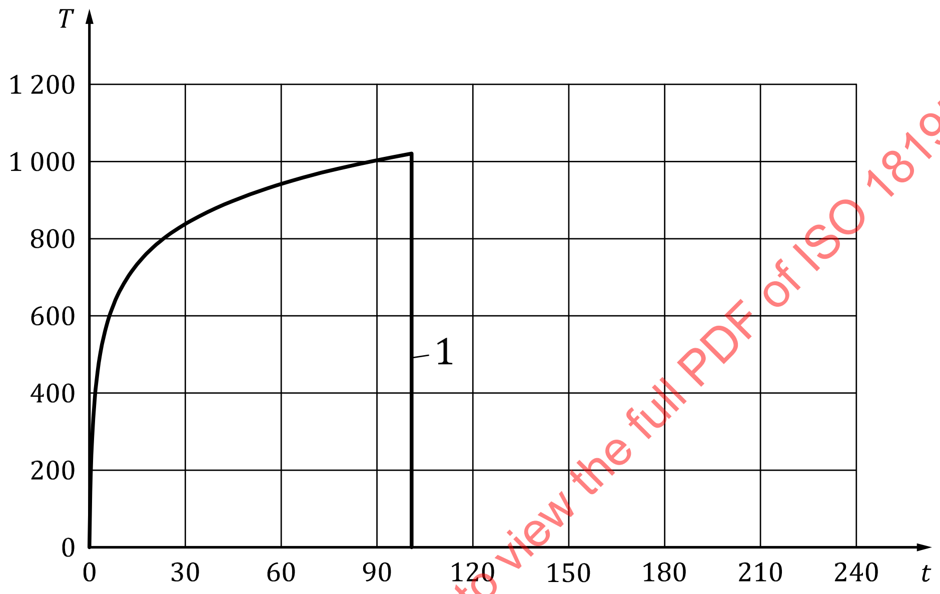
The temperatures that correspond to the plateau are generally not the criterion temperatures. It is not necessary to represent this plateau perfectly, but its duration shall be determined correctly. The aim is to correlate the temperatures close to the criterion adopted.

If the failure criterion is a temperature, it should be adapted to find a temperature close but slightly higher than the standard failure temperature, when it approaches the failure criterion adopted (conservatism).

6.4.5 Plotting performance curves from the reference curves

The first performance curve that may be plotted from the reference test is the conventional curve, even if it does not including the decay of the fire (see 6.7). Therefore, the standard time/temperature curve in ISO 834-1 is one of the performance curves until the failure criterion is reached [see Formula (1)].

This performance curve is represented in Figure 11.



Key

t time in min

T temperature in °C

1 time to reach the classification criterion

Figure 11 — Performance curve generated from the standard test

However, the actual fire temperature curves observed on confined fires representatives of NPP scenarios rarely follow the shape of the standard time/temperature curve; their rises are generally less sharp and their descents longer. It was therefore decided to define a set of curve profiles, known as alternate curves profiles (CFR: temperature Curve for Fire - Reference) in order to cover more situations. These curves, which are deliberately limited to 3 to reduce the number of calculations necessary, are proposed as guides for plotting the performance curves (however, other profiles for alternate curves may be envisaged). They are initially based on parametrical fire models described in Annex B of the European standard[42].

The alternate curve profiles are representative of:

— a fast fire (steep rise) and short decay (curve CFR C1A);

— a slow fire (slow rise) and slow decay (curve CFR C3A);

— an intermediate fire between the 2 previous curves (curve CFR C2A).

Analytically, the rise phases are given by the Formula (4):

$$\theta_g(t)=20+1\,325\left(1-0{,}324e^{-at}-0{,}204e^{-bt}-0{,}472e^{-ct}\right) \quad (4)$$

and the decay phases are linear with a slope β for each curve.

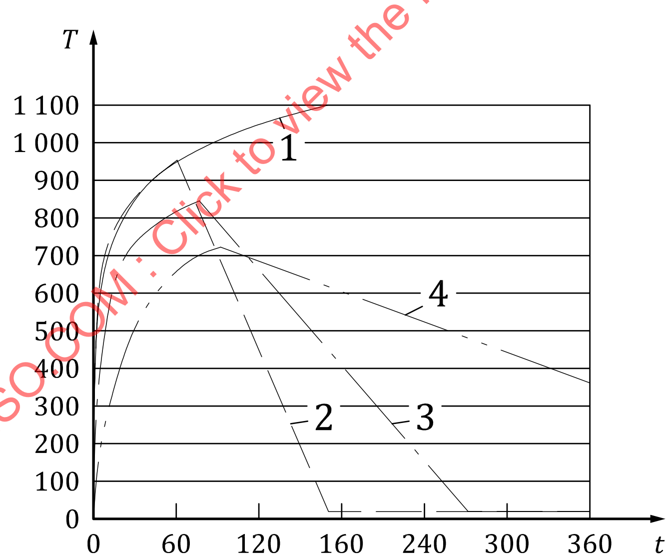
In this equation, t is the time in h and the coefficients a, b and c for each curve are shown in table 2.

Table 2 — Coefficients used to plot the CFR

	CFR C1A	CFR C2A	CFR C3A
a	0,211	0,082	0,026
b	1,790	0,692	0,218
c	20,009	7,739	2,433
β	-521	-224	-80

A performance curve is plotted on the basis of an alternate curve. For this, the duration of the spreading phase is increased or reduced so that the performance criterion adopted is reached without ever being exceeded. This means the duration of the spreading phase of the fire and ensuring that the performance criterion is not exceeded, by successive iterations of the model.

We therefore obtain the 3 performance curves including a decay phase, when the duration of the spreading phase is the following for the 3 curves C1A, C2A and C3A (e.g. on Figure 12: 58 min, 118 min and 183 min).



Key

t time in min

T temperature in °C

1 $T_{ISO\ 834}$

2 CFR C1A

3 CFR C2A

4 CFR C3A

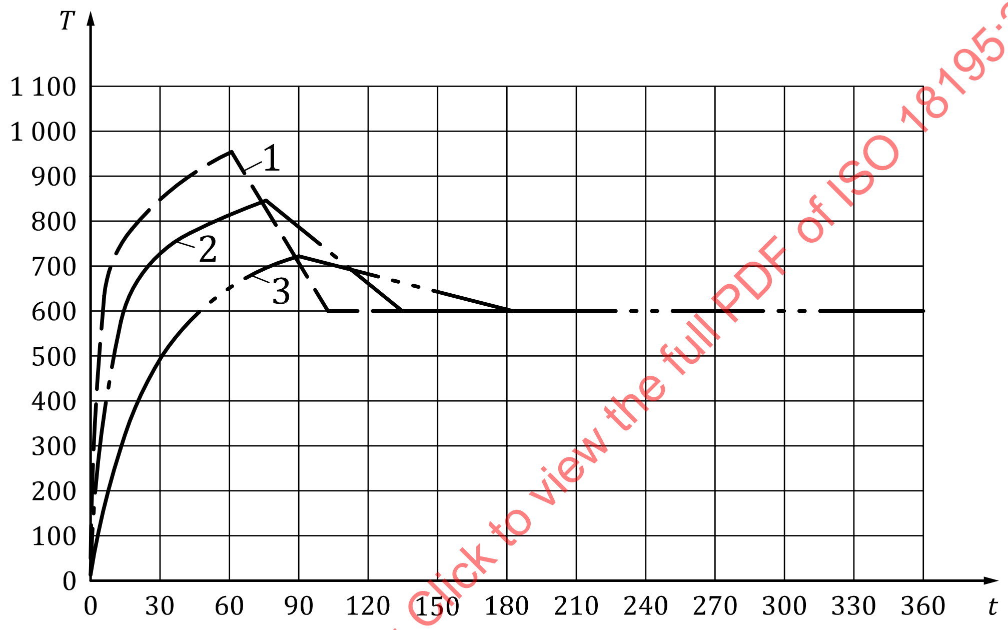
Figure 12 — Example performance curves (based on ISO 834-1)

6.4.6 Plotting "steady state" curves

In many situations, there is a set of conditions that, even if held indefinitely, would not cause the failure criterion to be met. When the unexposed face of the element has adiabatic boundary conditions, this set of conditions is identical to the failure criterion. The duration of the steady state curve shall be limited in case of material presenting a consumption effect or a specific risk of structural change at the considered temperature, by comparison to experimental feedback or by estimation of the resting material.

6.4.7 Plotting the performance diagram

The performance diagram is formed by the performance curves, which are truncated by the "steady state" temperature curve. An example of a performance diagram is given in Figure 13 for a single leaf door.



Key

t time in min

T temperature in °C

1 C1B

2 C2B

3 C3B

Figure 13 — Example of a performance diagram (single leaf door)

NOTE 1 Taking the "thermal inertia" of the partitioning element into account introduces a significant enhancement in relation to regulation performance.

6.5 Phase 2 BRANCH B: working out a new family system

Branch B is devoted to equipment belonging to a product family for which the causes of the fire resistance classification rating have not already been analysed.

6.5.1 Study approach for branch B

The successive steps required for branch B are as follows.

— Step 3B: This step consists of analysing several reports of fire resistance tests on products similar to that studied to identify the main causes leading to the loss of the fire resistance rating, for this product family. This step is carried out by extending step 1 (see 6.4.1) to all the products in the same family.

— Step 4B: Product modelling step, the approach is similar to step 3A for branch A.

— Step 5B: This step consists of performing an experimental test with a temperature/time curve lower than the standard fire temperature curve (ISO 834) and using a decrease phase to confirm the applicability of the present method to the product.

— Step 6B: Plotting the performance diagram for the product, the approach is similar to the step 4A for the branch A.

6.5.2 Experimental check (step 5B)

The test required for step 5B is carried out on a product for which the performance criteria have been found and the performance curves plotted.

Step 5B is intended to check the following experimentally:

— the overall behaviour of the product in a temperature/time curve less severe than the standard fire temperature curve (ISO 834);

— the main cause leading to the loss of the fire resistance rating and the criterion adopted for modelling;

— the modelling of thermal properties during the growth and decay phases;

— the applicability of the present method to the product.

The test procedure should be, with the exception of its thermal program, exactly the same as the fire resistance test carried out to classify the product, especially in terms of control of the furnace, pressure, measuring instruments, geometry, etc.

The test curve or thermal programme should have both a spreading phase and a decay phase. The following curve (CFE: Curve for Fire - Experimental) may be used; it has been plotted to meet the following criteria:

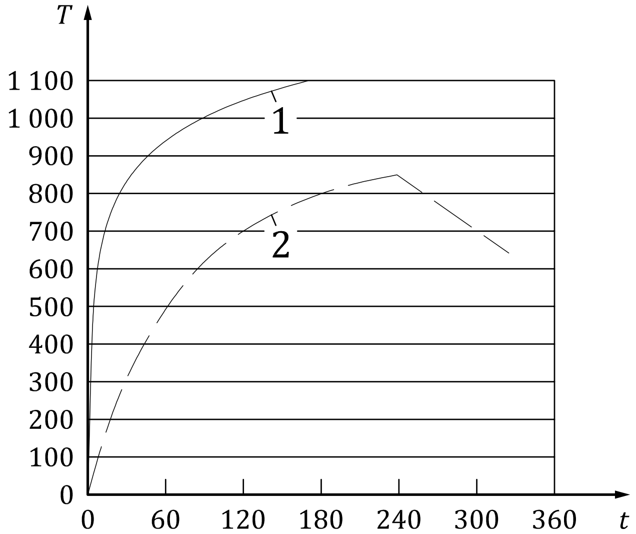
— Duration of the fire temperature curve between 2 h and 6 h (representative of fires controlled by ventilation);

— Decay of the fire after 4 h;

— Temperature of hot gases more than 600 °C for more than 4 h;

— Technically reproducible in the furnaces of fire resistance laboratories.

It may however, be modified according to the performance duration required. For instance, for a product reaching the failure criterion in less than one hour, the test curve duration should be reduced (see Figure 14).



Key

t time in min

T temperature in °C

1 ISO 834

2 CFE

Figure 14 — Temperature curve for supplementary experimental check (CFE)

This curve is characterised by Formulae (5) and (6), where *T* is the temperature in °C and *t* the time in h:

For $t < 3{,}96$ h:

$$T = 1\,553{,}3 \times \left[\begin{array}{l} 1 - 0{,}324 \times \exp\left(-0{,}2 \times 0{,}048\,42 \times t\right) - 0{,}204 \times \exp \\ \left(-1{,}7 \times 0{,}048\,42 \times t\right) - 0{,}472 \times \exp\left(-19 \times 0{,}048\,42 \times t\right) \end{array} \right] + 30 \qquad (5)$$

For $t > 3{,}96$ *h*:

$$T = -143{,}78 \cdot t + 1\,420{,}5 \qquad (6)$$

The test should then be analysed for:

— observations: behaviour similar to the standard test;

— performance criterion: main cause resulting in the product failure corresponds to the one identified for the step;

— measurements: application of the numerical modelling and check that the results are close to the experimental ones.

The calculation results may present certain differences with the experimental results, for example, the difference in the time required to reach the criterion may be approximately ten minutes, with a very similar temperature (a few °C). The result is acceptable if the same order of magnitude is obtained or if the analysis by calculation results in an unfavourable time (shorter).

6.6 Phase 2 branch C: specific characterization tests

The performance curves are determined for branch C when the analysis of the standard test does not easily produce a simple criterion for the failure of the product or if this criterion cannot be modelled. One or more appropriate tests should therefore be carried out to plot the performance curves.

The first step (3C) consists of performing specific tests to clearly identify the fire behaviour of the product and the conditions to reach the failure criterion.

If the criterion is reproducible through numerical modelling, the following steps may be carried out:

— Modelling of the product (step 3A);

— Check of the model by comparison with the results of the step 3C test (step 6C);

— Plotting the performance curves (step 4A);

— If not, the performance curves of the product shall be plotted experimentally (step 4D).

Since the approach for branch C includes principally experimental aspects, the expertise of an approved fire resistance laboratory shall be required to plot the performance curves for equipment that depends on branch C.

6.7 Alternative performance curves

At this stage it has to be noted that the most natural way to obtain performance curves of a given fire barrier is to test it experimentally to a specific fire temperature curve. As far as this test is performed in the same conditions and using the same failure criteria set that the standard test, any temperature/time curve can be validated in that way. Of course, this possibility will be rarely exploited due to the cost of such tests.

For instance, the standard test itself constitutes a performance curve for the barriers, as seen in 6.4.5, even if the lack of decrease phase limits its use.

An important point about the performance curve concept is that it does not guarantee the failure criterion will not be reached after the end of the curve duration, even if the fire has stopped, due to possible thermal inertia effect inside the product. This is particularity true for alternative curves ending brutally as the standard test does. For this reason it is recommended to provide significant steady state duration at the end of alternative performance curves in order to avoid such effects.

6.8 Performance curve diagram

The performance curve diagram is the collection of confirmed performance curves established for a given product.

6.9 Validation of the models

As the method is based on experimentation and modelling, the issue of model validation is important. The software employed shall be well-known and duly validated. Any possibility of comparison between modelling and available experimental data on a given product should be regarded by the applicators of this International Standard.

7 Uncertainty and sensitivity

This method deals with numerical simulation of fire and is therefore subject to uncertainties. Due to the complexity of the method, calculation of theoretical uncertainties is not possible and a sensitivity approach will be more practical. During a numerical simulation, uncertainties may come from parameters uncertainties, Model uncertainties or model Completeness uncertainties. Recommended considerations on this topic are those in ISO 9001:2015, Clause 4, that can be applied here.

The following aspects shall be taken into consideration to deal with the possible uncertainties of results and avoid significant effect in its application.

7.1 Use of average values (zone model vs. CFD model)

The method has been developed principally for zone models, and uses typical average values like average upper layer temperature.

This is justified because the present method provides an extension of the ratings obtained from the application of a fire resistance standard test. Those standards are based on the assumption that the time/temperature curve (ISO 834) developed in the standard furnaces encompasses typical fire situations. Thus it could be assumed that the standard is representative of generalized fires with similar duration, with no consideration to potential localized thermal effects. Condition in the furnace are quite homogeneous in temperature compared to a real fire and the time rating is credited for vertical or horizontal barrier not taking into account the location of the barrier in the real life.

On the other hand the thermal effects of the furnace include direct radiation heat transfer (burners and walls) because the hot gases are optically thin (generally propane burners) and it is not reflected by the air temperature only. On the contrary, fires encountered in NPPs generally produce optically thicker smoke. For this reason, the use of smoke layer average values is a better indicator of the global flux and temperature impact for comparison to the furnace conditions.

Of course local temperatures provided by zone models may be used (plumes, ceiling jet temps etc.) if a more conservative approach is intended for the qualification of fire barriers.

CFD may be used, adopting the same type of post-processed average zone values (see 5.3), considering that the local temperatures are more sensitive to uncertainties coming from the numerical model (meshing and geometrical representation and fluid dynamic and combustion calculation). Local temperature in the vicinity of the target (choosing the more conservative value of the two) can be an alternative if a more conservative approach is intended. Considerations including local flux and temperature could be another alternative, but they would require a complete analysis of the thermal behaviour of the fire barriers, which is not included in this document.

7.2 Uncertainties and sensitivities in fire temperature curve calculation

Numerical models shall be applied in their range of validity. As it is quite impossible to obtain quantitative accuracy, the conservatism introduced by the other aspects of the method will avoid the need for uncertainty evaluation: mass loss rates, reduction of volumes heat transfer surfaces, combustion efficiency, etc. Nevertheless it is recommended that the studies be completed with a sensitivity analysis avoid certain scenarios. For instance:

— Situation close to a PFL to PFG transition.

— Fire barriers directly exposed to a fire source. Ad hoc studies shall be necessary to treat situation where jet fires (typically hydrogen fires) could directly impinge upon fire barriers. The present method does not deal with this issue.

— Occasional fast slope fire sources in PFG situations. Generally the fire temperature curve slope does not play a direct role in the global fire duration, because the under-ventilated regime is quickly obtained for PFG fires. In cases where doubt remains, a complementary calculation based on the majority fire source may consolidate the study.

7.3 Uncertainties and sensitivities in the performance curve process

No safety factor is required for application of the performance diagram due to the conservative assumptions used during the design fire temperature curve process. No specific margin is introduced during the process of the performance curve determination. Nevertheless, two types of margins are implicitly present, with no quantitative evaluation:

The criteria used for the qualification remain unchanged from the fire resistance standards practice and maybe very conservative; for instance a criterion of a temperature increase of 140 °C (see Annex C) in average to evaluate a risk of propagation is very conservative. No current flammable material is presenting such flammability condition without flame exposure.

Comparison between fire temperature curve and performance curve generally shows important differences is the first stages of the fire, which generally gives significant safety margin.

Annex A
(informative)

Spreading criterion PFG/PFL (examples)

In this annex, examples are provided for the PFG/PFL criteria, based on the EDF experience for EPR NPP (EPRESSI method[39]).

A.1 PFG Room

The room satisfies PFG criterion if one or more of the following criteria (Table A.1) is reached in the room.

Table A.1 — PFG Criteria

Electrical cable fire PFG	Liquid fire PFG	Material fire PFG	Electromechanical equipment fire PFG
1) Presence of more than 3 superimposed racks of more than 3 m in length containing more than 400 kg of cables over 3 m. 2) Presence of 3 superimposed racks of more than 3 m in length containing more than 400 kg of cables over 3 m and the highest rack is less than 50 cm from the ceiling. 3) Presence of one vertical rack of more than 2 m high and less than 10 cm from a wall. 4) Presence of several vertical racks of more than 2 m high and less than 20 cm from each other.	5) Presence of at least 25 litres of fuel with rapid kinetics in rotating machines driven by electric motor, heat engine, or turbine. 6) Presence of more than 100 litres of fuel with high kinetics.	7) Presence of a fire load (other materials, see 5.4.4) of more than 4 300 MJ over 2 m^2 [a].	8) Presence of an open electrical cabinet with potential peak HRR of more than 1 MW.
a PFG is assume resulting from excessive concentration of combustible.			

A.2 PFL Room

The room satisfies PFL criterion if at least one of the following criteria (see Table A.2) is reached in the room:

Table A.2 — PFL Criteria

Electrical cable fire PFL	electromechanical equipment fire PFL	Liquid fire PFL	Material fire PFL
1) Presence of more than 2 cable racks posing more than 75 kg of cables over at least 1 m. 2) Presence of a vertical rack of more than 2 m in length, located parallel to a wall and less than 10 cm from the wall. 3) Presence of a route of several vertical racks of more than 2 m in length, less than 20 cm apart.	4) Presence of an electric cabinet or cubicle with openings for natural or forced convection cooling. 5) Presence of at least one cubicle not fitted with openings and >1 m in length.	6) Presence of storage of more than 25 liters of fuel with rapid kinetics.	7) Presence of a solid fire load (other materials, see 5.4.4) of more than 900 MJ on 2 m^2.

A.3 Neither PFG nor PFL room

Rooms where neither PFG nor PFL criteria are reached are said to be “neither PFG nor PFL.” The concentration of combustible mass in such rooms is not enough to generate a widespread fire. However, in so far as protective measures are concerned, when the total heat of combustion of the room is greater than $\left(960 \cdot \sqrt{A_T}\right)$ with A_T = surface of the walls of the room (excluding surface of its openings) (m^2), the room shall take the PFL criterion for the fuel with the highest heat of combustion in the room; if not, the room retains its neither PFG nor PFL classification, with no possibility of widespread fire developed from any point of origin.

Annex B
(informative)

Value examples for fire scenarios

B.1 Growth factors α

The growth factors depend on the type of combustible. Tables B.1 and B.2 below show recommended values of α for each scenario. It refers to the well-known T-square fire table (see Reference [53] appendix B).

Table B.1 — Recommended Values of growth factor α for fires, excluding cable fires

	Scenarios 1 and 2	**Scenarios 3, 4, 5**	**Scenarios 8 and 9**
	Flammable liquid fire	Electromechanical equipment fire	Fire of other materials
α (kJ·s^{-3})	0,187 6 (ultra fast)	0,002 9 (slow)	0,011 7 (medium)

Table B.2 — Example values of growth factor α for cable fires (source: EDF)

	Scenarios 6, 7: PFG or PFL cable fire		
	Horizontal cable racks		Vertical cable racks
	The last rack is less than 50 cm under the ceiling	The last rack is more than 50 cm under the ceiling	
α (kJ·s^{-3})	$\alpha = \alpha_{\text{ref1}} \frac{L}{5} \sqrt{\frac{\frac{M}{L \times n_{\text{rack}}} - 6}{16}}$	$\alpha = \alpha_{\text{ref2}} \sqrt{\frac{\frac{M}{L \times n_{\text{rack}}} - 6}{16}}$	α = 0,001 9
	— Coefficient α_{ref1} = 0,002 134 — Coefficient α_{ref2} = 0,000 198 12 — L: length of the rack in m — n_{rack}: number of racks — M: total mass of combustible in kg		

The number of racks should be between 3 and 8 for "PFG" cable fires and between 2 and 3 for "PFL" cable fires. If the number of racks is not known, the following values should be adopted by default: 3 racks for PFL and 4 racks for PFG. These values come from EDF experience[39].

B.2 Maximum pyrolysis rate

The maximum pyrolysis rate is a parameter that the user will have to fix in order to describe the potential fire. It represents the potential maximum mass loss rate for a given fire source (fully developed fire in unconfined conditions). In the calculation, this value will not necessarily be reached due to the ventilation conditions.

B.2.1 Scenarios 1, 3, 6 and 8: PFG type fire

In these scenarios, no maximum pyrolysis rate is given considering that the pyrolysis rate will be fixed only by the air flow rate passing through the openings. This steady state will be obtained by the fire model balance. The steady state obtained by calculation (CD in 5.4.5.6, Figure 6) may be less than the peak value observed during the growth phase (B in 5.4.5.6, Figure 6)

The steady state may be estimated by the following formula ([71] 3.6):

$$\dot{Q}_{max} = \dot{m}_{max} \times \Delta Hc$$

with

$$\dot{m}_{max} = \frac{\dot{m}_{airmax}}{\mathrm{St}} \cdot X_{0_2}$$

and

$$\dot{m}_{airmax} = 0{,}5 \times A_0 \times \sqrt{H_0}$$

Hence

$$\dot{m}_{max} = \frac{0{,}5 \times A_0 \times \sqrt{H_0}}{St} \cdot X_{0_2} \ \ (\mathrm{kg \cdot s^{-1}})$$

where

S_t is stoichiometric ratio of the fuel (g_{o2}/g_{fuel});

X_{0_2} is Oxygen ratio in the entering air (g_{o2}/g_{air});

$$A_0 = \sum_i A_{0i} \ \text{ and } \ H_0 = \frac{\sum_i H_{0i} \times A_{0i}}{A_0}$$

A_{0i} is surface of the vertical opening i of the room (m^2);

H_{0i} is height maximum of the vertical opening i of the room (m) = distance between the top of the opening and the floor of the room.

B.2.2 Scenario 2: PFL liquid fire

This scenario corresponds to a liquid pool fire.

The maximum rate of pyrolysis is assessed according to the following formula ([71] 3.1):

$$\dot{m}_{max} = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)S$$

where

$K\beta$ is product of the extinction coefficient of the flame K (m^{-1}) and a correction factor β;

$\dot{m}''_{\infty}$ is rate of surface vaporisation for an infinite diameter ($kg \cdot m^{-2} \cdot s^{-1}$);

D is equivalent diameter of the liquid surface (m);

S is surface of the layer of liquid (m^2).

The surface to be taken into consideration is either the collection surface (or surface of drains) when the liquid is located above a pedestal, as is the case of rotating machines with oil tanks, or the surface of the retention tank for liquids in storage. The characteristics $K\beta$ and $\dot{m}''_{\infty}$ can be obtained from references like [71].

For non-circular surfaces, the equivalent diameter corresponds to:

$$D = \sqrt{4S/\pi} \text{ (m)}$$

Example data for a fire of oil on a surface of 1 m^2[71]:

$K\beta$ = 0,7 m^{-1}

$\dot{m}_{\infty}$ = 0,039 kg·m^{-2}·s^{-1}

with

S = 1 m^2;

D_{eq} = 1,28 m

Hence $\dot{m}_{max}$ = .021 3 kg·s^{-1}.

B.2.3 Scenarios 4 and 5: electrical cabinet or cubicle fire (PFL)

The maximum power $\dot{Q}_{max}$ adopted for closed electrical cabinet or cubicle fires is 211 kW. This value, which is taken from report [73] (appendix G) is based on American experience feedback on electrical cubicle fires fitted with qualified electric cables (IEEE 383[72]). For open cabinets, the user should adopt a realistic value if there is supporting evidence for it. If not the maximum power is assumed to exceed 1 MW and therefore scenario 3 is adopted.

The rate of pyrolysis is determined by the following formula:

$$\dot{m}_{max} = \frac{\dot{Q}_{max}}{\Delta H_C} \text{[(kg·s}^{-1}\text{)}$$

where

$\dot{Q}_{max}$ is the maximum power of the fire source (kW);

ΔH_C is the Heat of combustion (kJ·kg^{-1}).

Here, the rate of pyrolysis ($\dot{m}_{max}$) for closed electrical cabinet is 0,012 9 kg·s^{-1} for a Heat Release Rate of 211 kW when the heat of combustion is taken to 16,4 MJ·kg^{-1} (PVC cables -[73][71] appendix G).

B.2.4 Scenario 7: cable fire (PFL)

The maximum pyrolysis rates of a cableway are calculated from correlations plotted from the results of cable fire tests carried out during different experimental campaigns. The main parameters involved in these correlations are as follows:

— Mass of fuel;

— Length of cable racks;

— Number of cable racks.

Position of the upper rack: top or bottom of the room (top if last rack is located less than 50 cm from the ceiling).

B.2.4.1 Horizontal cable trays

The following values for cable trays (Tables B.3 and B.4) are based on EDF experience and full-scale tests[39].

Case 1: the last rack is located less than 50 cm under the ceiling

Table B.3 — Values for coefficient β_1

Number of racks	β_1 (kg·s^{-1})
1	0,001 7
2	0,103 3
3	0,122 3
4	0,223 4
5	0,241 4
6	0,260 4
7	0,280 4
8	0,450 4

$$\dot{m}_{max} = \beta_1 \cdot \frac{L}{5} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}} \quad (\text{kg·s}^{-1})$$

where

L is length of the rack (m);

n_{rack} is number of racks;

M is mass of combustible cables (kg);

β_1 is pyrolysis rate coefficient (kg·s^{-1}).

(depending on the number of racks)

Case 2: the last rack is located more than 50 cm below the ceiling

Table B.4 — Values for coefficient β_2

Number of racks	β_2 (kg·s^{-1})
1 (no fire)	
2	0,043
3	0,06
4	0,069
5	0,075 2
6	0,083 2
7	0,091 2
8	0,103 9

$$\dot{m}_{max} = \beta_2 \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}} \text{ (kg/s)}$$

where

L is length of the rack (m);

n_{rack} is number of racks;

M is mass of combustible cables (kg);

β_2 is pyrolysis rate coefficient ($kg \cdot s^{-1}$).

B.2.4.2 Vertical cable racks

$$\dot{m}_{max} = \beta_3 \cdot n_{rack} \cdot \sqrt{\frac{\frac{M}{L \cdot n_{rack}}}{6}}$$

where

L is length of rack (m);

n_{rack} is number of racks;

M is total mass of combustible (kg);

β_3 is reference rate of pyrolysis (kg/s) ($\beta_3 = 0{,}028\ kg \cdot s^{-1}$).

B.2.5 Scenario 9: fire of combustible masses in storage (PFL)

The maximum power adopted for fires of combustible masses in storage is 317 kW. This value is taken from reference document [73].It corresponds to the average power levels measured during the fire tests carried out by Sandia National Laboratories for storage of heterogeneous fuels (cellulose, plastic, liquid, etc.):

$$\dot{m}_{max} = \frac{\dot{Q}_{max}}{\Delta H_C} \text{ } (kg \cdot s^{-1})$$

where

$\dot{Q}_{max}$ is maximum heat release of the fire source (kW);

ΔH_C is heat of combustion ($kJ \cdot kg^{-1}$).

B.3 Other characteristics of the fire source

The other characteristics of the fire source are given in Table B.5 for each scenario.

Table B.5 — Other characteristics of the fire source

Scenarios	**1 and 2**	**3, 4 and 5**	**6 and 7**	**8 and 9**
Type of fire source	Inflammable liquid fire	Electromechanical equipment fire	Cable fire	Fire of other materials
Reference fuel	oil	PVC	Cable	Wood
ΔH_C (kJ/kg)	46 400	16 400	16 000	18 000
Radiated fraction	0,34	0,4	0,4	0,4
Stoichiometric ratio (g_{O2}/g_{fuel})	3,61	1,408	1,408	1,418

The characteristics of others fuels can be found in relevant documentation like [71].

B.4 Summary of the complete fire scenario

Summary information for the different types of fires is given in Tables B.6 to B.10.

Table B.6 — Liquid fire

	Liquid fire ([71] paragraph 3.1)	
No. scenario	**1 (PFG)**	**2 (PFL)**
α (kJ·s^{-3})	0.187 6 (fire with very rapid dynamics)	
$\dot{m}_{max}$ (kg·s^{-1})	Fixed by the ventilation conditions	$\dot{m}_{max} = \dot{m}''_{\infty}\left(1-e^{-k\beta,D}\right)S$ $\dot{m}_{max}$ = 0,021 3 kg/s (oil)
$\dot{Q}_{max}$ (kW)	Fixed by the ventilation conditions	$\dot{m}_{max} = \dot{Q}_{max} \times \Delta H_C$ namely for an oil layer fire of 1 m^2 Q_{max} =988 kW
ΔH_C (kJ·kg^{-1})	46 400 (oil)	
Stoichiometric ratio (g_{O2}/g_{fuel})	3,61 (oil)	
Credited combustible mass (kg)	Total Combustible mass of the room = Total heat of combustion/ΔH_C	Liquid Combustible masses of the PFL type increased by the credited combustible masses likely to be present in the plume of the fire source

Table B.7 — Electromechanical equipment fire

	Electromechanical equipment fire		
No. scenario	**3 (PFG)**	**4: cabinet (PFL)**	**5: cubicle (PFL)**
α (kJ·s^{-3})	0,002 9 (fire with slow dynamics)		
$\dot{Q}_{max}$ (KW)	Fixed by the ventilation conditions	211 ([71][73]appendix G: qualified cables, fire in a bundle of cables)	
ΔH_C (kJ·kg^{-1})	16 400 (PVC[71] appendix G)		

Table B.7 *(continued)*

	Electromechanical equipment fire		
No. scenario	**3 (PFG)**	**4: cabinet (PFL)**	**5: cubicle (PFL)**
$\dot{m}_{max}$ (kg·s^{-1})	Fixed by the ventilation conditions	$\dot{m}_{max} = \frac{\dot{Q}_{max}}{\Delta H_C}$ namely for a PVC electrical equipment fire: $\dot{m}_{max}$ = 0,012 9	
Stoichiometric ratio (g_{o2}/g_{fuel})	1,408 (PVC[73][71] appendix C)		
Credited combustible mass (kg)	Total combustible mass of the room = Total heat of combustion/ΔH_C	10	35

Table B.8 — Cable fire for horizontal cable racks

	Cable fire for horizontal cable racks	
No. scenario	**6 (PFG)**	**7 (PFL)**
α (kJ·s^{-3})	The last rack is less than 50 cm under the ceiling $\alpha = \alpha_{ref1} \frac{L}{5} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}}$ with α_{ref1}=0,002 134 The last rack is more than 50 cm under the ceiling $\alpha = \alpha_{ref2} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}}$ with α_{ref2} = 0,000 198 12	
Nb_{rack}: number of racks	1 to 8	2 to 8
M: Mass of fire source (kg)	Combustible mass of PFG cables	Combustible mass of PFL cables
L: length of the rack (m)	length of the PFG cableway(m)	length of the PFL cableway (m)
$\dot{m}_{max}$ (kg·s^{-1})		The last rack is less than 50 cm under the ceiling: $\dot{m}_{max} = \beta_1 \cdot \frac{L}{5} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}}$ The last rack is more than 50 cm under the ceiling: $\dot{m}_{max} = \beta_2 \cdot \frac{L}{5} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}}$
$\dot{Q}_{max}$ (KW)	Fixed by the ventilation conditions	$\dot{m}_{max} = \dot{Q}_{max} \times \Delta H_C$

Table B.8 *(continued)*

	Cable fire for horizontal cable racks	
No. scenario	**6 (PFG)**	**7 (PFL)**
ΔH_C ($kJ \cdot kg^{-1}$)	16 000 (PVC cables average – source : EDF)	
Stoichiometric ratio (g_{o2}/g_{fuel})	1,408 (PVC -[71] – appendix C)	
Credited combustible mass (kg)	Total combustible mass of the room = Total heat of combustion/ΔH_C	Combustible mass of PFL cables plus the credited combustible masses likely to be present in the plume of the fire source

Table B.9 — Cable fire for vertical cable racks

	Cable fire for vertical cable racks
	7 **(PFL)**
α (kJ·s^{-3})	0.001 9
$\dot{m}_{max}$ (kg·s^{-1})	$\dot{m}_{max} = \beta_1 \cdot \frac{L}{5} \sqrt{\frac{\frac{M}{L \cdot n_{rack}} - 6}{16}}$
Nb_{rack}: number of racks	1 to 2
M: Mass of the fire source (kg)	Combustible mass of PFL cables
L: length of the rack (m)	length of the PFL cableway
$\dot{Q}_{max}$ (KW)	$\dot{m}_{max} = \dot{Q}_{max} \times \Delta H_C$
ΔH_C (kJ·kg^{-1})	16 000 (PVC cables/PVC - EDF)
Stoichiometric ratio (g_{o2}/g_{fuel})	1,408 (PVC -[73] – appendix C)
Credited combustible mass (kg)	Combustible mass of PFL cables plus the credited combustible masses likely to be present in the plume of the fire source

Table B.10 — Other materials

	Fire of other materials	
No. scenario	**8** **(PFG)**	**9** **(PFL)**
α (kJ·s^{-3})	0,011 7 (fire with average dynamics)	
$\dot{Q}_{max}$ (KW)	Fixed by the ventilation conditions	317 ([71][73]appendix G: Fuel transient)
ΔH_C (kJ·kg^{-1})	18 000 for of the wood ([73][71] appendix G)	
$\dot{Q}_{max}$ (kg·s^{-1})	Fixed by the ventilation conditions	$\dot{m}_{max} = \frac{\dot{Q}_{max}}{\Delta H_C}$ namely for a wood fire $\dot{m}_{max}$ = 0,017 7 kg·s^{-1}[53]
Stoichiometric ratio (g_{o2}/g_{fuel})	1,418 (for wood)	
Credited combustible mass (kg)	Total combustible mass of the room = Total heat of combustion/ΔH_C	Combustible mass material plus the credited combustible masses likely to be present in the plume of the fire source

Annex C
(informative)

Loss of classification criteria : examples

The following are issued from EPRESSI method[39] resulting from French feedback.

Table C.1 — Loss of classification criteria examples

Family	Loss of classification criterion identified and checked by test	Type of modelling
Door	$\Delta T > 140$ °C on the unexposed surface of the leaf	1D
Damper	C1: $\Delta T > 180$ °C 70 mm from the framework (wall mounted)	2D
	C2: $\Delta T > 180$ °C to 20 mm from the anchor flange (flush mounted)	
	C3: $\Delta T > 180$ °C on the anchoring	1D
Penetration seal	C1: $\Delta T > 180$ °C on the surface of the seal (side not exposed to the fire)	3D
	C2: $\Delta T > 180$ °C on through elements if non-combustible (e.g.: metal tubes)	
	C3: $T > 240$ °C on the cable 25 mm above the caulking	
Wrapping	T (inside the sheath) = PVC cables : 188 °C SH cables (control): 320 °C SH cables (power): 350 °C	2D
Housing	$T = 180$ °C on the unexposed surface of the housing (160 °C inside the housing)	1D
	$T = 188$ °C ambient in the housing 1 350 mm above the floor	2D
Ventilation duct	$\Delta T > 140$ °C on the section of ducting 25 mm from the bead	2D
Smoke clearance duct	$\Delta T > 180$ °C in section s2 120 mm from the caulking	Temperature of the air along the centre line of the ducting (balance)
		1D conduction in the thickness of the duct

Annex D
(informative)

Example of performance diagram of a cable fire-wrap

D.1 Standard fire test: Cable wrap (EDF)

An example of a fire-resistant cable wrap is depicted in Figures D.1 through D.3. All the electric cables are halogen free and representative of French EPR (EDF).

ISO 834 test for 2 fire resistant wrap:

— Normal “non-aged” cable wrap (the cable wrap is directly installed and fire tested);

— Dried “aged” cable wrap (cable wrap is first installed in a drying oven, then after fire tested).

Figure D.1 — Electric cable raceway with fire-resistant wrap

The aim of the aging is to represent the state of the stabilized wrap, a significant time after its installation, considering that some water or aerosol may be present at the beginning.

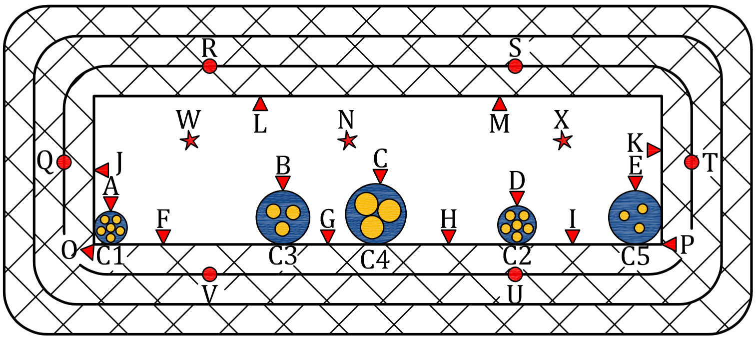
All temperatures readings were taken on a single measurement section with:

— three thermocouples of ambient air within the wireway;

— a temperature sensor on the surface of each cable;

— four temperature sensors in the wireway between the cables.

This annex is given as an application example. Neither the wireway characteristics nor the thermocouple location, for instance, should be regarded as part of the requirements of this International Standard.



MPF 120 : "aged" cable wrap																								
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
s1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	45	46

MPF 120 : "non-aged" cable wrap																								
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
s1	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	47	48

Landmark	**Location**
A-B-C-D-E	cable surface
F-G-H-I-J-K	wireway inner surface
O-P	wireway inner angle
L-M	wireway inner upper side face
N-W-X	inner ambient temperature
Q-R-S-T-U-V	between first and second wrap layer protection

Key

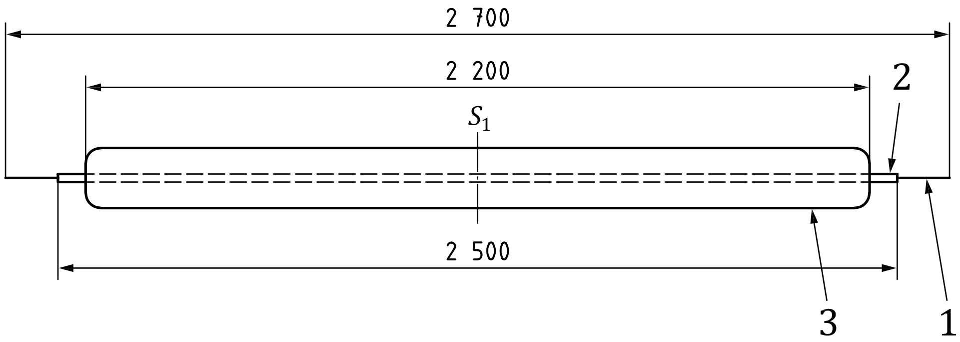
C1-C2 =10*1 mm^2 I&C Cables

C3 =3*16 mm^2

C4 =3*35 mm^2 Power cables

C5 =3*2,5 mm^2

Figure D.2 — Temperature sensors location



Key

1 cable

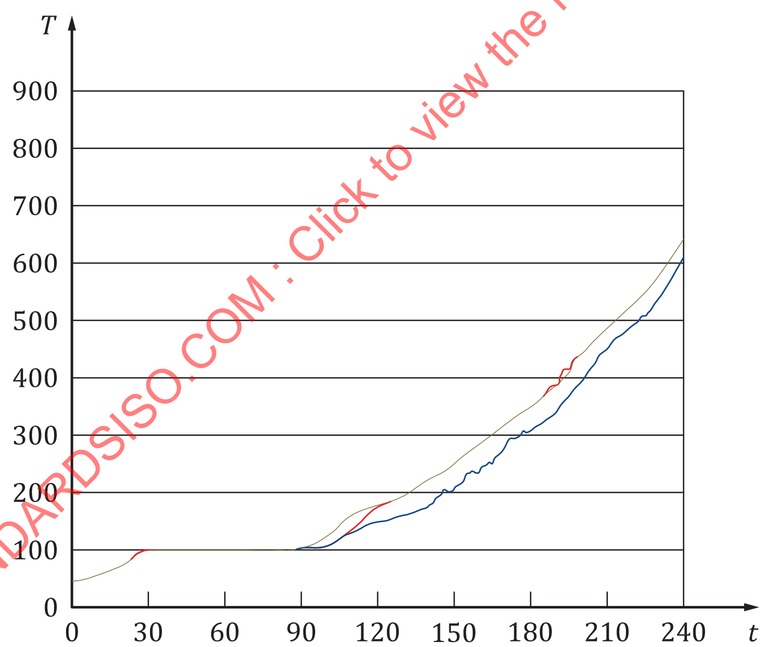
2 cable tray

3 fire protection

Figure D.3 — Wrap dimensions

D.2 Analysis of the standard test

Figures D.4 and D.5 depict evolution of the ambient temperature inside a "non-aged" cable wrap and an "aged" cable wrap, respectively.



Key

t time in min

T temperature in °C

Tc 36

Tc 47

Tc 48

Figure D.4 — Evolution of the ambient temperature inside a "non-aged" cable wrap