FIRE SAFE EUROPE

# Classification system for the smoke toxicity of fire-exposed construction products

Technical document

# Table of Contents


**1. Introduction** ....... **5**

**2. European Classification system for Constructions products** ....... **7**

*2.1. Construction Products Regulation* ....... *7*

*2.2. Classification of smoke toxicity system* ....... *9*

**3. Incorporating product smoke toxicity into the Construction Product Regulation** ....... **10**

*3.1. Fire conditions and gases to be considered* ....... *14*

*3.2. Classification principle* ....... *16*

*3.3. Safe zone* ....... *17*

**4. Input for Fire Safety Engineering (FSE)** ....... **19**

*4.1. FSE basis and approaches to smoke toxicity* ....... *19*

4.1.1. Relative method ....... 19

4.1.2. Absolute method ....... 19

*4.2. FSE methodology and toxicity effect* ....... *19*

4.2.1. Safety Objectives ....... 19

4.2.2. Functional requirements for occupant safety objectives ....... 19

4.2.3. Performance criteria ....... 20

4.2.4. Design fire scenarios and design fires ....... 21

*4.3. Chemical species yield and sources* ....... *22*

4.3.1. Occupants evacuating the building ....... 22

4.3.2. Occupants remaining in the building: relative place of safety ....... 22

**5. Test methodology to determine smoke toxicity classification** ....... **24**

**6. Recommendations** ....... **26**

**References** ....... **27**

## List of abbreviations

| | |
|---|---|
| ASET | Available Safe Escape Time |
| CACC | Controlled atmosphere cone calorimeter |
| CIT | Conventional Index of Toxicity |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CPD | Construction Products Directive |
| CPR | Construction Products Regulation |
| FEC | Fractional Effective Concentration |
| FED | Fractional Effective Dose |
| FIGRA | Fire Growth Rate |
| $FIPEC_{Horizontal}$ | Fire Performance of Electric Cables, Horizontal reference scenario |
| FSE | Fire Safety Engineering |
| HCN | Hydrogen Cyanide |
| $H_2O$ | Water |
| ISO | International Organization for Standardization |
| LDPE | Low density polyethylene (also known as polythene®) |
| PA | Polyamide (also known as Nylon) |
| PMMA | Polymethylmethacrylate |
| SMOGRA | Smoke Growth Rate |
| PP | Polypropylene |
| PVC | Polyvinyl Chloride |
| RSET | Required Safe Escape Time |
| SBI | Single Burning Item |
| SDC | Smoke Density Chamber |
| SSTF | Steady State Tube Furnace |
| TOXGRA | Toxicity Growth Rate |

## List of figures

Figure 1 Schematic describing the CPD/CPR classification system (based on Notified Bodies Position Paper) ........ 7
Figure 2 Relationship between Dose and Concentration ........ 10
Figure 3 Toxicological hazard matrix ........ 13
Figure 4 Mode of action & relevance to human - method of determination - intra/interspecies variability........ 15

## List of tables

Table 1 ISO 9705 performance criteria........ 8
Table 2 ISO classification of fire stages, extracted from ISO 19706[9] ........ 11
Table 3 Criteria matrix ........ 16

## 1. Introduction

Statistics have shown that inhalation of toxic smoke is the leading cause of death in fires, and also the major cause of injuries. Yet fire smoke toxicity is not considered in the European regulatory framework for construction products. According to a recent UK Parliament POST Note on Fire Safety of Construction Products[1], in England, from April 2016 to March 2017, fire services attended approximately 162 000 fires that led to 261 deaths and around 7,100 casualties. Most of these fatalities occurred in dwellings (82%) and were accidental. Deaths were mainly due to being overcome by smoke or gas (38%), burns (25%), or a combination of both (16%). In addition, the remaining 21%, which were unclassified at the time of reporting, are likely to show the same distribution, taking the toxicity deaths above 50% of the total[2].

When a fire starts, it most often initiates in a specific item of content. The fire will then spread to other contents of the room plus the building structure. Often within minutes (depending on room geometry, ventilation and contents) the entire room will be involved in the fire. Openings in walls and floors for services (pipes, cables, ducts, etc.) which are left open or are not sealed with an appropriate and approved firestopping system will contribute to the spread of fire and smoke throughout the building.

The European Commission is aware of the importance of the issue. In 2016, a study was mandated to evaluate the need to regulate the toxicity of smoke produced by construction products in fires. In January 2018, the European Commission published the final report of this study[3] (Toxicity Study in the rest of the document). The conclusions of the report state that "clear definition of terminology is lacking" and "the type and format of data collected varies across Member States, and, at present, statistics on smoke toxicity are not collected and therefore the effectiveness of potential measures cannot be assessed." At the same time, the report concluded that "if the case for regulation were proven, then an agreed European system for testing and classification, with regulations and requirements at national level is favoured."

Considering the significant consequences caused by exposure to toxic smoke during fire incidents, it is important to ensure a robust method to determine the toxicity of smoke for construction products and further classify products in accordance with the toxicity of the effluents released during fires.

The purpose of this document is to outline the principles of a classification system for smoke toxicity that can be easily incorporated into the construction products regulation and the current classification framework for reaction to fire.

In order to regulate it is first necessary to define toxic hazard classification criteria. The methodology must be robust. Smoke toxicity changes significantly as the fire develops from initial ignition to a fully developed fire. The system therefore needs to be able to incorporate the different stages of a fire in order to provide the information needed to assess the smoke toxicity of construction products during fires.

The smoke toxicity released from construction products during fire shall be determined using a common test method that can be correlated to the reference fire scenario, fire in a room, currently defined in the European classification for construction products. A consideration of test methods suitable to demonstrate compliance will be the topic of a further document.

In addition, the introduction of a classification system with robust and well defined criteria for smoke toxicity together with a common test method for determine the toxicity of effluents released during fires are valuable tools to provide data regarding yields of toxicants released from different materials and construction products. Such data can be further used in fire safety engineering analyses during the design phase.

In accordance with the current classification for reaction to fire, this document only considers acute exposure to toxic effluents for occupants and first responders. The chronical effects of exposure to toxic smoke shall be further investigated and developed in addition to the classification methodology proposed in this document.

## 2. European Classification system for Constructions products

### 2.1. Construction Products Regulation

*"The Construction Products Directive (CPD) entered into force within the Member States of the European Union (EU) in December 1991. The primary purpose of the CPD was to remove technical barriers to trade for product manufacturers within Europe through the development and adoption of European Technical Specifications (harmonised product standards and European Technical Approvals) and so enable product manufacturers to sell their products throughout Europe by complying with a single common European Technical Specification recognised and accepted by all Member States, rather than having to test and comply with different national standards in each Member State.*

*In July 2013, the Construction Products Regulation (CPR) came into force and as such, for construction products covered by a harmonised product standard, CE marking became mandatory and in such cases, fire performance is declared in accordance with European fire classifications."*[3]

The CPD/CPR philosophy is based on the premise that it is impossible to predict installed end use product fire performance from a knowledge of the fire properties of the materials/components used in the fabrication of products. It is therefore necessary to define intermediate scales with the resulting classification based on demonstrated correlations between the scales.

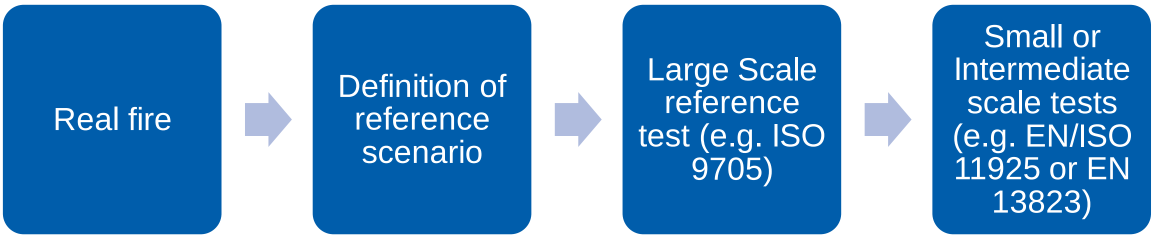


**Figure 1 Schematic describing the CPD/CPR classification system (based on Notified Bodies Position Paper[5])**

The philosophy behind the CPD is described in a Position Paper by the Group of Notified Bodies (NB-CPR/SH02-16/657r4)[5]. It explains that a building fire is considered too poorly defined to be treated as a whole but must be broken down into critical scenarios. Specifically, this Paper defines fire in a room, fire in linear products (such as pipes or cables) and façade fires as needing special consideration. The large-scale reference test relating to fire in a room is the room corner test (ISO 9705). The need for specific Reference Scenarios is also noted in the introduction to ISO 9705 – "*This method is not suitable for sandwich panel building systems, pipe insulation and façades for which specific ISO standards (i.e. ISO 13784, ISO 20632 and ISO 13785, respectively) are available".*

The European classification scheme is derived from performance in the ISO 9705 room (Table 1). The values of Fire Growth Rate, Room Corner ($FIGRA_{RC}$) were found to correlate with the defined performance criteria. “Flashover” is the transition point to a fully developed room fire, resulting in very rapid fire growth to other spaces in the building.

**Table 1 ISO 9705 performance criteria**

| Class | Performance criteria | $FIGRA_{RC}$ /W $s^{-1}$ |
|---|---|---|
| **A2** | **No flashover for 300 kW burner** | **<160** |
| **B** | **No flashover for 300 kW burner** | **<600** |
| **C** | **No flashover for 100kW burner** | **<1500** |
| **D** | **Flashover time > 2min for 100kW burner** | **<7500** |
| **E** | **Flashover time < 2min for 100kW burner** | **>7500** |

The room corner test is considered too large for classification purposes and an intermediate scale test (Single Burning Item – EN13823) was found to give a satisfactory correlation with the Room Corner Test.

In 2007, Sundstrom[4] published details of the implementation of the system including the important correlation factors for wall lining products and the linear products (pipe insulation and cables). For both linear products, ISO 9705 was deemed unsatisfactory and modified reference scenarios and classification tests have since been developed.

## 2.2. Classification of smoke toxicity system

In the current European classification system for construction products the toxicity of fire effluents is not assessed, thus the materials are not evaluated and classified in respect to the toxicity of smoke released during a fire event. The definition of a European classification on toxicity of effluents from construction products involved in fire must be linked to the relevant scenario. For construction products under the Construction Product Regulation the reference scenario (Position Paper by the Group of Notified Bodies NB-CPR/SH02-16/657r4[5]) has been defined and is the basis for the reaction to fire and the fire resistance classification system.

The Toxicity Study[3] final report shows different possible approaches. The first is related to the potential danger of smoke leaking into or being generated in areas that are considered to be safe zones and /or escape routes. The second is related to the national regulations already in place (even if they are limited). Many of those regulations are based on the principle of protection of occupants from smoke and fire. The requirements are oriented to specific types of building and limited in term of gases considered.

The Toxicity Study also demonstrates that the toxicity of fire effluents cannot be considered separately from the other fire performances of construction products: this has to be considered as a global approach.

Based on the conclusion of the study, the classification system for smoke toxicity shall include the following three fire safety objectives:

1. Restrict the generation of toxicants where it is possible, as toxicants could enter safe zones and escape routes.
2. Ensure safe escape of all occupants.
3. Ensure the safety for firefighters and other emergency service personnel.

Amongst the factors to take into consideration in quantifying the hazard include the environment, availability of oxygen, thermal attack, flow conditions and surface areas available for combustion, and the chemistry of the combustion can proceed along different routes and produce species in very different quantities. Toxic gas emissions depend on:

- Nature of fuel
- Location and mode of production of species
- Availability of air (ventilation condition) – sometimes expressed as equivalence ratio or fuel to air ratio
- Heat flux at the surface and heat transfer within the material

In addition, the proposed classification must be applicable to all types of construction products.

## 3. Incorporating product smoke toxicity into the Construction Product Regulation

The European classification system for reaction to fire incorporated in the Construction Product Regulation (CPR) considers a single reference large-scale fire test, Room Corner Test, which should represent the parameters for toxic gas production and fire growth.

The determination and quantification of combustion gases generated by the Room Corner Test is an established method, ISO 16405:2015, which could readily be incorporated into the CPR system. Data from this test would be used to define classification criteria but would subsequently be repeated rarely[5]. In a process directly analogous to reaction to fire, the actual fire effluent product classification would be made on smaller scale tests which give a satisfactory correlation with the reference scenario classification criteria.

The key factors needed for toxic hazard determination are the related parameters concentration and dose of effluent to which the population is exposed, defined as the Fractional Effective Concentration (FEC) and Fractional Effective Dose (FED). The concentration can be calculated from the compartment volume and product mass loss which is a function of the initial mass of product and its combustibility.

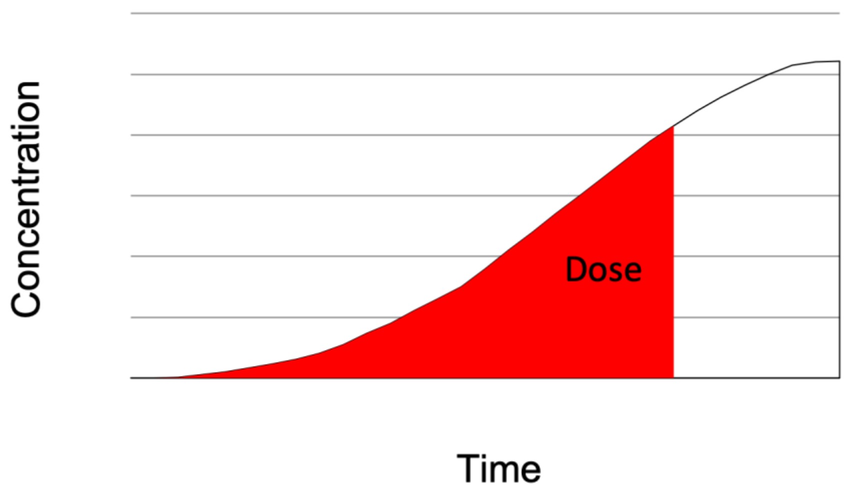


**Figure 2 Relationship between Dose and Concentration**

Smoke toxicity increases significantly with under-ventilation. If there is enough fuel, fire growth is often limited only by the availability of oxygen. Fires in buildings, such as an apartment, even with the doors open, quickly change from well-ventilated to under-ventilated flaming, as the rate of burning becomes controlled by the air replenishment rate, which predominates for the duration of the fire[6]. This occurs when the volume of flame is around 5% of the volume of the room.

The stages of a fire have been classified by ISO[7]. While some real-life fires may be represented by a single fire stage, most fires progress rapidly from stages 2 to 3a or 3b.

**Table 2 ISO classification of fire stages, extracted from ISO 19706[9]**

| Fire Stage | Heat /kW $m^{-2}$ | Max Temp /°C | | Oxygen % | | Equivalence ratio | CO/$CO_2$ ratio | Combustion Efficiency % |
|---|---|---|---|---|---|---|---|---|
| | | **Fuel** | **Smoke** | **In** | **Out** | $\phi$ | | |
| **Non-flaming** | | | | | | | | |
| 1a. Self-sustained smouldering | n.a. | 450 - 800 | 25 - 85 | 20 | 0 - 20 | - | 0.1 - 1 | 50-90 |
| 1b. Oxidative, external radiation | - | 300 - 600 | | 20 | 20 | - | | |
| 1c. Anaerobic external radiation | - | 100 - 500 | | 0 | 0 | - | | |
| **Well ventilated flaming** | | | | | | | | |
| 2. Well ventilated flaming | 0 to 60 | 350 - 650 | 50 - 500 | ~20 | 0 - 20 | <1.0 | <0.05 | >95 |
| **Under ventilated Flaming** | | | | | | | | |
| 3a. Low vent. room fire | 0 to 30 | 300 - 600 | 50-500 | 15 - 20 | 5 - 10 | >1.0 | 0,2 - 0,4 | 70 - 80 |
| 3b. Post flashover | 50 to 150 | 350 - 650 | >600 | <15 | <5 | >1.0 | 0,1 - 0,4 | 70 - 90 |

The different stages of the fire are described in the international standard ISO 19706 (Table 2). The equivalence ratio in Column 7 describes the relative amount of fuel and air necessary in the flame region for a complete combustion of the fuel. An equivalence ratio of 0.5 means there is twice as much air needed for complete combustion of the fuel mass, while an equivalence ratio of 2 means there is twice as much fuel as air available for complete combustion.

For non-flaming stages of the fire (1a, 1b, and 1c) the equivalent ration specified in the current version of ISO 19706 are difficult to correlate in practical application because smouldering fires is a combustion phenomenon inside a porous material and the air to fuel ration inside the material, where combustion occurs, is difficult to establish.

For flaming stages of the fire (2, 3a and 3b), as described in Table 2, theoretical equivalence ratios for well-ventilated fires may range between 0,5 - 0,7, while equivalence ratio for under-ventilated fires may range between 1,5 - 2.0. The flashover period characterised by a rapid transition from well-ventilation to under-ventilation into a very short period, often a few seconds, may occur at equivalent ratio between 0.7 to 1.5. For practical reasons, the flashover period is included in stage 3a of the fire since the rapid increase of the temperature and heat release rate will often cause turbulences in the flaming areas leading to under-ventilated combustion.

The table describes stages in experimental fire tests, which reflect stages of real unwanted fires. For smoke toxicity, the most important stages are:

**1 Non-flaming:**

- **1b Oxidative external radiation**, normally encountered as smouldering, which produces a small volume of toxic smoke. This is particularly relevant to scenarios such as smoking in bed, where a victim, especially if incapacitated, may succumb to the toxicity of the smoke being produced in the immediate vicinity. In addition, smouldering combustion may occur in construction products, such as wooden structures, cables, wood fibre boards, et al., which could fill escape routes with toxic effluents resulting from smouldering combustion.

**2 Well-ventilated flaming** – this usually produces a medium volume of relatively low toxicity smoke.

**3 Under-ventilated flaming:**

- **3a Low ventilated flaming** – this produces a larger volume of much more toxic smoke than well-ventilated flaming (the majority of UK fire deaths result from such fires[8]);
- **3b Post-flashover** – this produces an even larger volume of highly toxic smoke and is usually associated with major fire disasters.

In absence of data on which of the aforementioned fire stages is most harmful, it is essential to consider these four fire conditions in the assessment of smoke toxicity. Only methods capable of replicating the most toxic, under-ventilated fire stages are suitable for such an assessment. All four fire stages: 1b, 2, 3a and 3b, should all be assessed, and the worst case determined based on the quantity of smoke produced during combustion and yield of toxicants shall be further used for the smoke toxicity classification, as indicated in the below matrix. Intuitively, Stage 3b should be in the top right of the matrix, but all stages need to be assessed as product may behave quite differently during different stages of fire.

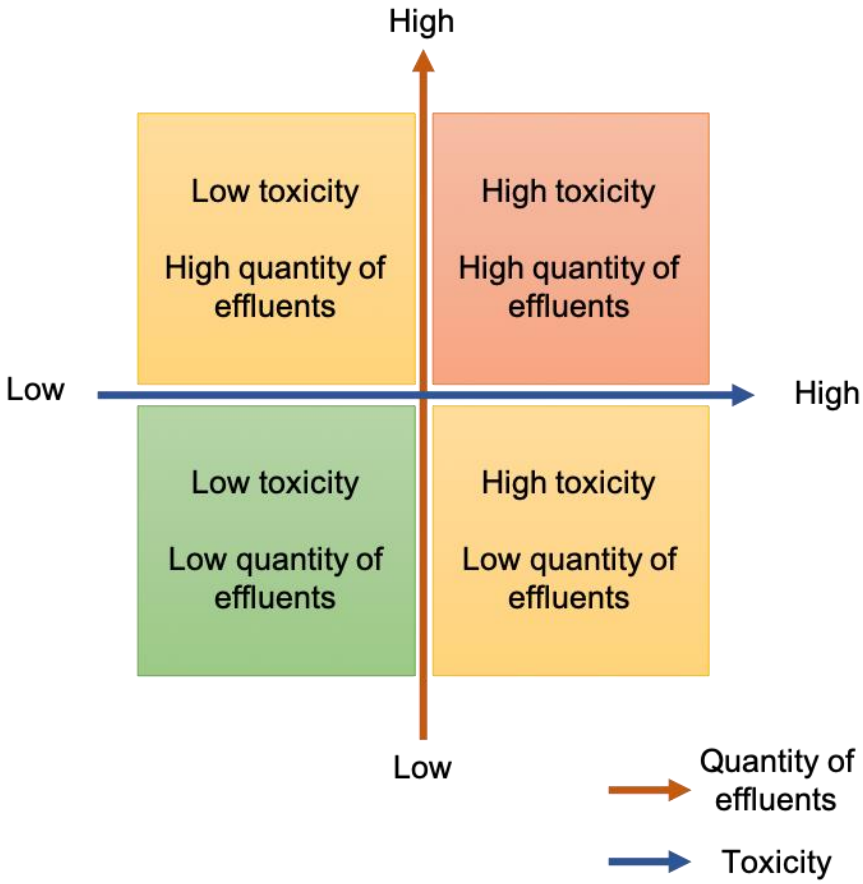


**Figure 3 Toxicological hazard matrix**

In terms of the room corner test, ISO 9705, the compartment volume is defined (20,7 $m^3$). The sample surface area is likewise defined[i] (31,7 $m^2$). Because the compartment has a single doorway, if the fuel is sufficiently combustible, flaming will soon become ventilation-controlled, leading to the higher toxicity of under-ventilated flaming. Currently the classification criterion is based on the time to flashover.

The pipe insulation reference scenario ISO 20632 utilises the ISO 9705 compartment but with a special product installation. In the development of this method it was observed that flashover was not common in the reference scenario for pipe insulation as the surface area of exposed pipe insulation is limited during the test[ii]. As a result, classification criteria are based on pre-flashover fire development parameters. Indeed, there is a case to modify the criterion from “flashover” to “flashover or fully developed”. This is a conservative modification and a de facto recognition of the current situation. In addition, it has been noted that flashover is not the predominant fire spread

[i] Including ceiling, excluding wall with door opening
[ii] This is largely a function of geometry with heat release (HR) increasing proportionally with flame spread (FS) whereas for surface products HR α $FS^2$.

mechanism in European buildings[2] with most fire deaths occurring in fires that did not flashover[8].

The principal cable reference scenario, the Fire Performance of Electric Cables, Horizontal reference scenario, ($FIPEC_{Horizontal}$), is not based on ISO 9705. It is a relatively open test with no obvious defined volume. As with pipe insulation products, the way cables are installed means they rarely exhibit flashover. Again, classification criteria are based on fire development parameters.

Several experts have commented on the importance of content primarily in the early stages of a building fire. Although outside the scope of this document it is noted that ISO 9705 tests[9] have been made on various building contents and the test could clearly be used to generate performance criteria for content products.

### 3.1. Fire conditions and gases to be considered

The Toxicity Study[3] does not specify which gases should be considered when assessing the toxicity of smoke for construction products involved in fire. The smoke toxicity assessments in International and European standards consider two types of gases, asphyxiants and incapacitating irritants[10].

- Asphyxiant gases
    - Carbon monoxide
    - Hydrogen cyanide
- Irritant gases
    - Hydrogen chloride
    - Hydrogen bromide
    - Hydrogen fluoride
    - Sulphur dioxide
    - Nitric oxides
    - Aldehydes: acrolein, formaldehyde
    - (Others: isocyanates, ammonia, etc)

The second step to define classification parameters is to identify the endpoint: incapacitation or lethality. Incapacitation, when the victim can no longer affect their own escape, is the most logical endpoint to use for ensuring life safety, but death was traditionally easier to measure consistently in animal subjects. Considering the objectives defined in the CPR basic work requirement II: Fire safety: *"(d) occupants can leave the construction works or be rescued by other means",* incapacitation should be used as the end point in preference to lethality.

There are a number of toxicity classification systems designed for occupational safety and emergency response (such as after an accident at a chemical plant). Most of these assume constant concentrations of toxicants and are based on historical animal exposure data. These include AEGL, NOAEL etc.

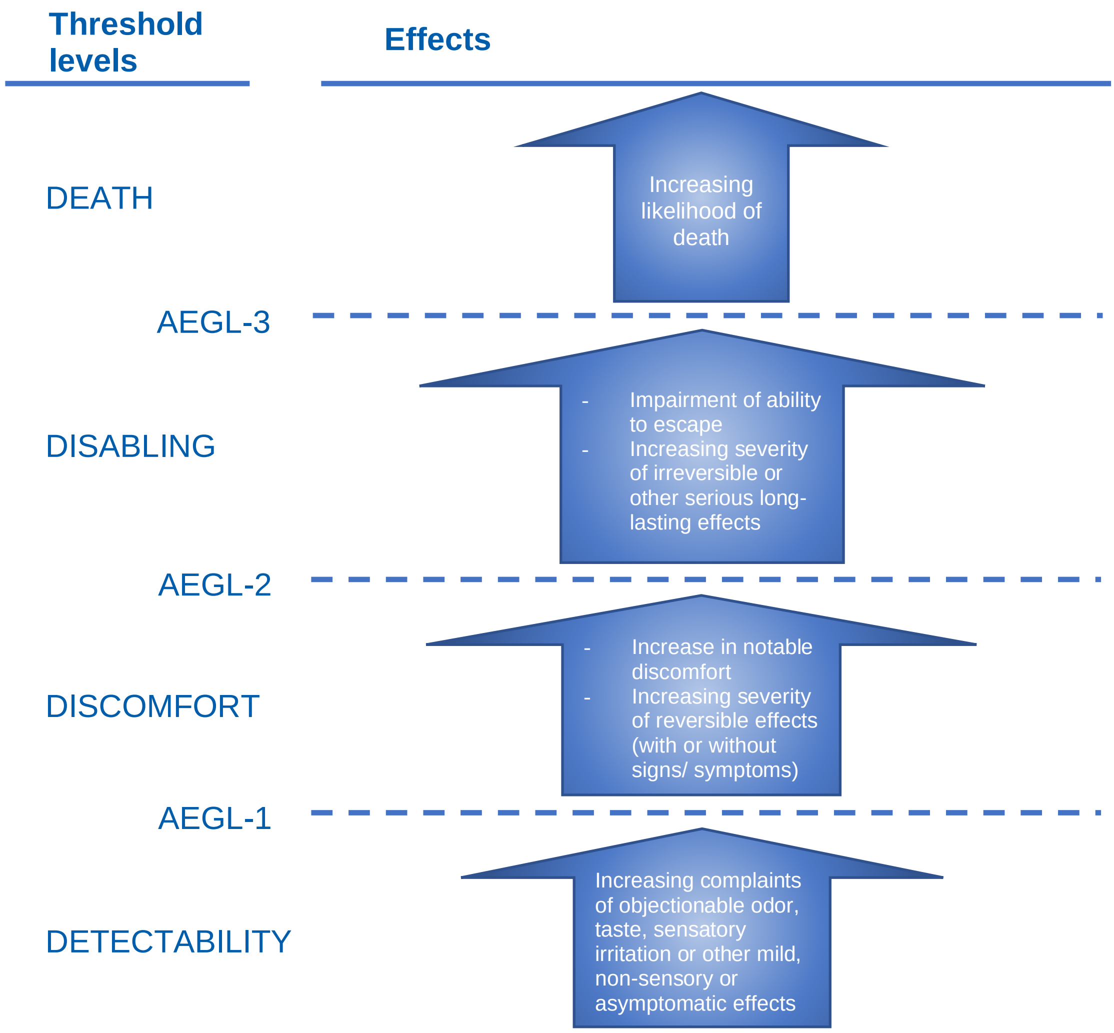


**Figure 4 Mode of action & relevance to human - method of determination - intra/interspecies variability**[11]

As an example of a classification system, the European railway sector has developed classification criteria based on this concept: The criterion is the Conventional Index of Toxicity (CIT).

CIT = [Precursor Term] x [Summation Term]

The "precursor term" is a model parameter that describes the fire model including the area of the products that is perceived to burn and the volume in which the fire effluents flow, while the "summation term" assesses the overall toxicity of the individual components. Unfortunately, the railway toxicity test relies on a test method which can only replicate well-ventilated flaming, where the rate of burning varies throughout the test, giving different values for peak and cumulative toxicity. While it could be argued that railway fires do not become under-ventilated when passengers are exposed to their effluent, the same could not be said of building fires.

Due to the complexity and diversity of building designs, defining performance criteria that will consider the enclosure volume, the ventilation and other influencing factors: Precursor Term and additional safety margins, shall be decided on by fire regulators at national level.

Based on a similar principle but considering only the "summation term" and taking into account the development of the reaction to fire Euroclasses for construction product, three parameters are identified for the classification of the toxicity of fire effluents from construction products:

- Toxicity index: $Tox_{ind,t} = \sum_i Ci / RCi$
  - Where Ci: is the concentration of the gas I in the fire model (7 gases)
  - RCi: is the reference concentration of the gas i
- The toxicity index being expressed as 2 parameters at a given time defined in regard of the reference scenario:
  - $Tox_{ind\ peak}$ peak value and
  - $Tox_{ind}$ cumulative values,

## 3.2. Classification principle

The classification criteria are evaluated on the basis of the criteria matrix considering 3-level classification:

**Table 3 Criteria matrix**

| | Low toxicity | Medium toxicity | High toxicity |
|---|---|---|---|
| *$Tox_{ind,peak}$ (FEC)* | < n1 | n1 ≤ $Tox_{ind,\ peak}$ < n2 | ≥ n2 |
| *$Tox_{ind}$ (FED)* | < n3 | n3 ≤ $Tox_{ind}$ < n4 | ≥ n4 |
| Worst case is considered for the classification meaning the Tox is defined by the higher value of FEC or FED | Tox1 | Tox2 | Tox3 |

Note: The decision on which values of n1, n2, n3 and n4 should be adopted is the responsibility of the European Commission. They could also, if they deem it necessary, adopt a delegated act to establish which fire reaction class of material would need to be tested for smoke toxicity, for example, the European Commission could decide, following the logic of the Euroclass system, to have a smoke toxicity index of Tox1 to

Tox3, but only for Euroclasses A2 to E, just like it is the case for smoke and burning droplets

In addition, the reference test will permit growth rate parameters (FIGRA, SMOGRA and TOXGRA) to be determined and any corresponding correlations to be identified.

The proposed building product classification system will certainly have the potential to classify "content" products.

### 3.3. Safe zone

The classification principles described in this document intend to ensure that the toxicity of smoke released during fires by materials and construction products is evaluated with the general purpose of ensuring that occupants are not exposed to high level of toxic gases. The classification for smoke toxicity can be applied complementary to the current European classification for reaction to fire and/or resistance to fire.

Following example showing how the proposed classification principles can be applied in practice by regulators and engineers.

ISO TS 29761 defines Required Safe Escape Time (RSET) (how long it takes to escape) and Available Safe Escape Time (ASET) (how long before the escape route is untenable)[12]. The values of RSET will depend on occupant characteristics, building characteristic and fire characteristics on the mobility of the occupants and the size and complexity of the building. The value of ASET will depend on several factors, including the generation of heat and smoke and particularly the toxicity classification of the building products.

In the design of a building, primarily means of escape (such as stairwells and corridors) and designated safe zones where people await to be rescued by the fire service must be free of smoke and toxic gas. The objective in the case of primarily means of escape and safe zone is to keep people who have reached the safe zones to be protected from smoke toxicity. The classification of construction products and building elements shall consider the danger of toxic gases leaking into or being generated in areas that are considered safe zones and/or escape routes.

The fire classification for construction products and building elements will be a reaction to fire classification with additional criterion for the toxicity related to emission of toxic gases from the unexposed side inside a safe zone. Building elements with fire separating function will also have fire resistance classification.

Examples:

For linings and finishing materials for walls and ceilings, the classification could be presented as following:

- Corridors: Class B-s1,d0,tox2
- Stairwell lobby and designated safe zones: Class B-s1,d0,tox1
- Stairwell: Class A2-s1,d0,tox1

For non-loadbearing elements with fire separation function or parts of works and products, the classification could be presented as following:

- Corridors: EI 60 / B-s1,d0,tox2
- Stairwell lobby and designated safe zones: EI 60 / B-s1,d0,tox1
- Stairwell: EI 90 / A2-s1,d0,tox1

## 4. Input for Fire Safety Engineering (FSE)

### 4.1. FSE basis and approaches to smoke toxicity

FSE is applied to analyse the fire safety level of a construction project, with two different approaches:

- A relative method that consists of comparing two designs, generally the prescriptive one and the alternative solutions.
- An absolute method that consists of analysing the level of safety of a design.

#### 4.1.1. Relative method

The relative method consists of comparing two designs (more or less complex). One fulfils the regulation. The second does not satisfy the prescriptive regulation and shall be justified considering this solution does not increase the fire risk compared to the prescriptive solution. For different fire safety objectives, fire safety criteria can be used. For this approach, if toxicity is used as an assessment criterion, data for both solutions should have the same uncertainty. The design fire scenarios that are assessed for both solutions will also have similar levels of uncertainty. The design fire scenarios will depend on both the contents and the construction products of the building.

#### 4.1.2. Absolute method

The absolute method includes analysing the design solutions with regard to the fire safety level. We can refer to ISO 23932 "general principles" to understand the process of FSE application. There are four main important steps identified in the method:

- Definition of objectives
- Definition of functional requirements
- Definition of performance criteria
- Selection of design fire scenarios and design fires

Toxicity may be included in performance criteria, according to the functional requirements. The assessment methodology will then include toxicity assessment based on the other stages of the analysis.

### 4.2. FSE methodology and toxicity effect

#### 4.2.1. Safety Objectives

The general fire safety objectives are defined[13,14,15] by:

- Safety of people: occupants, firefighters, neighbours
- Safety of goods: building, contents, operations
- Safety of environment: water, air, soil

#### 4.2.2. Functional requirements for occupant safety objectives

For the safety of occupants, the functional requirements should be addressed:

- Maintain the tenability conditions for evacuation of occupants from the room of fire origin

- Maintain tenability in egress routes for evacuation of occupants
- Maintain tenable conditions in the safe zone where occupants are waiting to be evacuated
- Maintain tenable conditions in rooms where occupants remain during all the fire duration (no evacuation).

All of these functional requirements should include the effect of toxicity in the assessment of tenability.

Maintaining tenability for fire fighters is a fundamental requirement of every building design and fire safety engineering analyses. However, the current fire-fighting procedures imply that fire fighters enter areas filled with smoke only using breathing apparatus to ensure that they are not exposed to the acute effects of toxic and irritant gases released during fires. Tenability criteria regarding exposure of fire fighters to toxic smoke is not further addressed herein.

### 4.2.3. Performance criteria

The functional requirements highlight two different situations for the toxicity impact of the tenability conditions:

- Short exposure time during evacuation of occupants.
- Longer exposure time for occupants awaiting evacuation after reaching a safe zone or awaiting fire extinction in their escape route. The ability of occupants to maintain awareness for decision making and performing specific tasks must be considered for specific conditions like control rooms and fire marshals.

ISO TC92 SC3 "Fire threat to people and the environment" is generally regarded as the foremost authority on smoke toxicity. ISO 13571 details performance criteria for both kind of exposure and ISO TR 13571-2 shows examples of application. ISO 13571:2012[16], gives estimates for the tenability limits in a fire, based on the four hazards of asphyxiation, irritancy, loss of visibility, and heat exposure. This allows a Fractional Effective Dose (FED) to be calculated for the asphyxiant gases HCN and CO, and a Fractional Effective Concentration (FEC) for the incapacitation irritants (HCl, HBr, HF, $SO_2$, $NO_x$, organoirritants etc). When either FED or FEC equal 1, the equations predict that 50% of the exposed population will be unable to escape (be incapacitated). In a real fire the gas concentrations increase rapidly, and often exponentially. Therefore, the expression for FED is the sum of steps of concentration x time reflecting the increased concentration with fire growth. Specific performance criteria for short and long-time exposure can be established in fire safety engineering analyses considering the methodology and data provided in ISO 13571:2012 for determining the FED and FEC. The engineering analyses shall also consider appropriate safety factors for the specific applications.

The FED value is determined based on the time interval persons are exposed to the toxic effect of the smoke. The time interval is dependent on the application and shall be conservatively selected to represent the time people are located within an area where toxic smoke can enter. The time interval for calculating FED value can range from a couple of minutes, required for a person to walk through a corridor filled with toxic smoke before reaching a safe stairwell, to several hours in cases where occupants need to wait in a safe zone or different fire compartment, defend in place strategy, before being rescued by the fire service.

**Equation 1** FED model taken from ISO 13571 shows the Fractional Effective Dose (FED)

$$X_{FED} = \sum_{t_1}^{t_2} \frac{\varphi_{CO}}{35\,000} \Delta t + \sum_{t_1}^{t_2} \frac{\varphi_{HCN}^{2,36}}{1,2 \times 10^6} \Delta t$$

where

| | |
|---|---|
| $\varphi_{CO}$ | is the average concentration, expressed in $\mu l \cdot l^{-1}$, of CO over the time increment, $\Delta t$; |
| $\varphi_{HCN}$ | is the average concentration, expressed in $\mu l \cdot l^{-1}$, of HCN over the time increment, $\Delta t$; |
| $\Delta t$ | is the time increment, expressed in minutes. |

The terms containing $\varphi_{CO}$ and $\varphi_{HCN}$ in Equation 1 at each time increment are to be multiplied by a frequency factor, $v_{CO_2}$ to allow for the increased rate of asphyxiant uptake due to hyperventilation. The frequency factor $v_{CO_2}$ shall be determined in accordance methodology in ISO 13571.

**Equation 2** FEC model from ISO 13571 shows the Fractional Effective Concentration (FEC) of sensory irritants in the fire effluent which prevent escape.

$$FEC = \frac{[HCl]}{IC_{50,HCl}} + \frac{[HBr]}{IC_{50,HBr}} + \frac{[HF]}{IC_{50,HF}} + \frac{[SO_2]}{IC_{50,SO_2}} + \frac{[NO_2]}{IC_{50,NO_2}} + \frac{[acrolein]}{IC_{50,acrolein}} + \frac{[fomaldehyde]}{IC_{50,fomaldehyde}} + \sum \frac{[irritant]}{IC_{50,irritant}}$$

The terminology used here is specific to ISO.

### 4.2.4. Design fire scenarios and design fires

The choice of design fire scenarios and design fires are a very important task within FSE application. ISO 16733 provides a selection of design fire scenario and design fires. Scenarios include details about the fire development and smoke spread:

- Location of the fire
- Nature of combustible
- Ventilation history of the fire (open, semi-ventilated, confined…)

From this information, design fires for each design fire scenario can be defined to include:

- Rate of heat release: thermal effect
- Particles yield: visual obscuration
- Chemical species yield: toxic effect

The three inputs to the scenario allow assessment of the effect on life-threatening:

- Thermal effect
- Visual obscuration
- Toxic effect: with differentiation between asphyxiants and irritants with interaction between these threats.

The annexes of ISO TR 13571-2 compare the different effects on tenability showing which prevail in different situations. Even when these examples are not relevant to the scenario under consideration, they may help in selecting which effects are life threatening (for example when the visual obscuration is more critical than the toxicity).

## 4.3. Chemical species yield and sources

The situation of occupants who are evacuating the building must be differentiated from the situation of occupants who reach a safe zone or remain in their original compartment.

### 4.3.1. Occupants evacuating the building

The occupants evacuating the building face conditions of compromised tenability as the fire develops, driven by fire involving:

- The content of the building
- The construction product of the building

The common perception is that the initial fuel source is the content. The flammability of the construction products is generally regulated following prescriptive rules for limiting the fire development. In cases where the combustible contents of the building are limited, such as a building open to the public, or well known, such as a hotel, then the fuel source of the contents can be characterized in detail. Thus, the characterization of construction products may also be taken into account in detail. For example, exhibitions, conference centres, large public halls etc. where the content is limited and generally clearly identified, increases the contribution of reaction-to-fire data, including toxic product yields. However, the toxic effects are not regulated in most countries.

Assessment of the toxic effect requires knowledge of the yields of each toxic chemical species and combustible product under the anticipated conditions of heat and ventilation. In the absence of detailed knowledge of the contents there will be greater uncertainty about the chemical species yield (and then of the overall toxicity).

### 4.3.2. Occupants remaining in the building: relative place of safety

Occupants remaining in the building awaiting fire extinguishment or to be rescued by the fire service, either located into safe zones or into their fire compartments, shall be protected from exposure to fire effluents. The design of the building needs to ensure that fire and toxic smoke does not spread to safe zones or other fire compartments where occupants might be located awaiting fire service intervention.

So, reduction of tenability conditions in the safe zone or in the compartment can come from:

- Transfer of smoke and hot gases from the fire to the safe zone through openings;
- Production of chemical species and heat release from the internal (unexposed) face of the compartment walls. Since flames accelerate the conversion of fuel to $CO_2$ and $H_2O$, such non-flaming pyrolysis is likely to produce a smaller volume of more toxic smoke.

Estimates can be made in order to identify the critical threat. For example, preventing leakage of fire effluent by active positive pressurisation of the compartment or safe zone limits the assessment to the chemical species released by the unexposed (internal) face of the walls and other components. In that case, toxicity measurements made during fire resistance tests with additional measurements on gases from the unexposed face would be the input to the assessment models.

## 5. Test methodology to determine smoke toxicity classification

Any method of assessing smoke toxicity must show a clear relationship to the large-scale fire scenario it is aiming to replicate. In the case of most construction products within the CPR, the reference scenario it needs to replicate is the ISO 9705 Room. For direct comparison between bench-scale fire tests and large-scale fire behaviour, the fuel-to-air ratio of the fire must be known. The easiest method of comparison arises when steady state or quasi-steady state test methods are used, as these allow definitive fuel-to-air ratios to be determined, resulting in repeatable and reproducible toxic product yields for almost all materials under individual fire stages.

Unfortunately, there is a limited amount of data available showing the toxic product yields from well-defined materials in large-scale tests. In particular, there are relatively few under-ventilated large-scale test data sets are available that have a known fire condition (in terms of fuel-to-air ratio).

The data presented from the European Commission funded TOXFIRE project[17] is one of the best large-scale data sets available. Their use of a "phi meter" to measure the fuel-to-air equivalence ratio during their ISO 9705 room test[18] testing allowed for the establishment of fire condition in terms of fuel-to-air ratio, making it an ideal data set to be used for bench scale test comparisons.

The initial stages of flaming in the ISO 9705 room are adequately represented by the Single Burning Item (SBI) test EN 13823 for Euroclass A2 to D. Other methods have more limited applicability, for example, bomb calorimetry for A1 and A2, and ISO 11925 for E. This should make the SBI the most obvious choice of method for assessment of smoke toxicity within the CPR. Its suitability for the quantification of smoke toxicity was assessed experimentally. Unfortunately, it proved unsuitable for such assessment for the following reasons:

- It could only replicate a well-ventilated fire scenario, the least toxic type of fire.
- The test measures FIGRA which is a good predictor of the flammability behaviour leading to flashover in the Room Corner Test. However, it couldn't replicate under-ventilated flaming, the most toxic type of fire.
- The large air flow through the exhaust duct, necessary to ensure operator safety, means that for many less-flammable products the toxic gases in the exhaust duct are below the detection limit of most analysers.
- Steady state burning conditions are not established for most materials, and mass loss is not routinely measured, so toxic product yields are not directly available from the test.

It is therefore necessary to evaluate alternative fire test methods that can be used to evaluate the smoke toxicity of construction products. Fire Safe Europe's technical report on "*Test methods for smoke toxicity classification of fire-exposed construction* *products*"[19] describes different test methods that could be considered for analyzing smoke toxicity of construction products. Considering all pros and cons, the report indicates that the Steady State Tube Furnace (ISO/TS 19700) is the most promising test method for such analyses and therefore relevant to be used as complementary bench-scale test method to the Single Burning Item (SBI) test.

## 6. Recommendations

The route to incorporate the regulation of product fire effluent hazard (toxicity) within the CPR has been outlined:

1. Three levels of fire effluent hazard (toxicity) Tox1, Tox2 & Tox3 should be defined.
2. Effluent toxicity performance criteria should be established using the current reference scenarios with the addition of effluent identification and quantification by means of ISO 16405 together with specific methods for evaluated aldehydes and isocyanates.
3. The approach to acute toxicants should be on the basis of asphyxiant and irritant gases:
    a. Asphyxiant
        i. Carbon monoxide
        ii. Hydrogen cyanide
    b. Irritant gases
        i. Hydrogen chloride
        ii. Hydrogen bromide
        iii. Hydrogen fluoride
        iv. Sulphur dioxide
        v. Nitric oxides
        vi. Aldehydes: acrolein, formaldehyde
        vii. Others

        Note: Numerous other irritant species can be formed in fires. The range of other species selected for analysis shall be broad enough to cover those species that can reasonably be expected to be released, based on the knowledge of the composition of the material.
4. The existing FIPEC cable reference scenarios use high ventilation which may render these scenarios unsuitable to establish cable fire effluent hazard criteria. The cable industry should be requested to consider this issue.
5. The existing classification tests are well-ventilated and therefore may be unsuitable for assessing smoke toxicity (see section 6).
6. There are a number of bench-scale classification test methods which correlate with ISO 9705. This topic will be addressed in a future document.

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