

Plastics — Guidance on fire characteristics and fire performance of PVC materials and products used in building applications

Draft for DTR ballot

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

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Introduction

Fire safety is an essential consideration in building design regardless of the type and nature of products used. Effective measures need to be taken to prevent or reduce the likelihood of fires that may result in casualties, injuries or property damage.

National codes and regulations are the basis of such fire safety measures. Technical details are given in standards and related documents, referred to as specific documents or incorporated in the said codes or regulations. Such details are particularly important when performance based behaviour is concerned. A specific case is the European Construction Products Regulation (Regulation (EU) N° 305/2011) [77], which specifies that products need to be tested and classified regarding their fire performance according to the EU harmonised classification systems for reaction to fire and for resistance to fire.

The construction industry makes significant efforts to protect society from the dramatic consequences of fires. As a result, 1% – 8% of total construction costs are spent on fire safety measures. These costs are directly dependent on the type of building and can increase considerably for sensitive buildings like schools and theatres. In the case of shopping centres, fire safety measures can amount to 10% of total building costs.

Plastic products are increasingly specified by architects and used by builders. They contribute to greater energy efficiency, cost savings and to a more comfortable and safer environment. The role of plastics in fire safety needs to be addressed despite the fact that they are considered as a major combustible contributor only in less than 15% of fires.

Plastic materials or products can be tailored to meet specific needs and to reduce their contribution to the propagation of a fire. Some families of plastics, such as halogen containing polymers like PVC, inherently have superior fire performance. The same performance can be achieved or even improved with other plastics by:

- Adding flame retardants
- Covering them with less combustible layers

Each type of building has its own specific potential fire hazards and fire risks linked to the permanent elements of the building (i.e. construction products and overall design) but also to its content including furniture, papers, clothes, domestic and leisure articles. Fire hazard and fire risk are also linked to the proper use and installation of construction products in the building structure. This is also valid for PVC and for plastic materials in general, which, like all other construction materials, have to be used in the correct applications and under appropriate conditions.

NOTE: Data from various market surveys show that only 10 to 15% of all plastics contained in a private house are in construction products. 85 to 90% of plastics are brought into the building by the occupants in, for example, furniture (including e.g. wooden furniture containing minor plastics elements), decorations, household and media appliances, clothes, toys and packaging. This means that although PVC is a significant component of many construction products, other combustible materials often comprise a more important potential source of fuel, in particular in private houses.

A fire usually involves a combination of different combustible and non-combustible materials. Organic materials (including all plastics, wood and other carbon containing materials) produce a mixture of gaseous substances (making fire smoke always hazardous) in addition to a certain degree of heat release.

As fire is a complex phenomenon, the type and quantity of materials involved are only two of the various parameters influencing the development and consequences of a fire. The other factors that come into play include building design, location, potential ignition sources and other fire scenario parameters.

Fire tests results relate only to the behaviour of test specimens under the particular conditions of the test. They are not intended to be the sole criterion of assessing the potential fire hazard of the product in use.

This Technical Report provides information on the fire characteristics and fire performance of PVC based materials and products used in building applications. It is to be considered as a documentary and technical reference document for any entity interested in fire safety in building and construction, when products containing PVC are concerned, including at the design or pre-building phase.

The intended audience for this Technical Report includes but is not necessarily limited to:

- Materials and products manufacturers
- Building designers, specifiers and architects
- Building owners and managers
- Fire fighters and investigators
- Public health authorities
- Fire testing laboratories

1 Scope

This Technical Report provides information on the fire characteristics and performance in fire tests of PVC materials and products for use in building applications.

This Technical Report illustrates a number of suitable applications incorporating primarily PVC materials, including unplasticized PVC (PVC-U), plasticized (or flexible) PVC (PVC-P) and chlorinated PVC (PVC-C) based products. Except where otherwise stated, there is no restriction with reference to the content of PVC (in terms of quantity and composition) in the products mentioned in this document.

This Technical Report draws attention to the limits of applicability or the unsuitability of some standard fire test methods for certain applications of PVC based products in buildings.

NOTE: This Technical Report applies to products during their use phase in the building and does not apply to the manufacturing phase of plastic products. It does neither apply to general safety measures applicable to the installation phase nor to the dismantling or the demolition phase of the building.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition (including any amendments) applies.

ISO 472: Plastics - Vocabulary

ISO 13943(2017): Fire safety - Vocabulary

IEC 60695-4: Fire hazard testing - Part 4: Terminology concerning fire tests for electrotechnical products

NFPA Glossary of terms

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 472, ISO 13943, ISO 26367-1, IEC 60695-4 and the following apply. Some terms and definitions from vocabulary standards are repeated in this document for sake of readability.

3.1

composite

solid product consisting of two or more distinct phases, including a binding material (matrix) and a particulate or fibrous material

solid product consisting of two or more layers (often in a symmetrical assembly) of, for instance, plastic film or sheet, normal or syntactic cellular plastic, metal, wood or a composite in accordance with definition in 2.182.1, with or without adhesive interlayers

[SOURCE: ISO 472:2013, Definitions 2.182.1 and 2.182.2]

3.2

compound

intimate mixture of a polymer or polymers with other ingredients such as fillers, plasticizers, catalysts and colorants.

[SOURCE: ISO 472:2013, Definition 2.184]

Note to entry: the terms "formulation" and "composition" are sometimes used as synonyms

3.3

fire effluent

totality of gases and aerosols, including suspended particles, created by combustion or pyrolysis in a fire.

Note to entry: For the purpose of this Technical Report, fire effluent also includes run-off water generated during fire-fighting activities.

3.4

fire safety engineering

application of engineering methods to the development or assessment of designs in the built environment through the analysis of specific fire scenarios or through the quantification of risk for a group of fire scenarios

[SOURCE: ISO 13943:2017, Definition 3.149]

3.5

flash ignition temperature

minimum temperature at which, under specified test conditions, sufficient flammable gases are emitted to ignite momentarily on application of a pilot flame

Note 1 to entry: Compare with the terms ignitability, minimum ignition temperature and spontaneous ignition temperature (see ISO 13943).

Note 2 to entry: Flash ignition temperature refers to the ignition temperature determined for solid specimens on application of a flame to the specimen, for example in a test method such as ISO 871. Flash point refers to the temperature to which a flammable liquid must be heated for its vapours to ignite.

Note 3 to entry: The typical units are °C.

[SOURCE: ISO 871:2006, Definition 3.1]

3.6

heat release

thermal energy produced by combustion

Note to entry: the typical unit is J.

[SOURCE: ISO 13943:2017, Definition 3.205]

3.7

ignitability

measure of the ease with which a test specimen can be ignited, under specified conditions

[SOURCE: ISO 13943:2017, Definition 3.212]

Note to entry: also known as ease of ignition

3.8

plastics products

articles or stock shapes of plastic materials for any type of application

[SOURCE: ISO 11469:2016, definition 3.2]

3.9

plenum

compartment or chamber to which one or more air ducts are connected and that forms part of the air distribution system

[SOURCE: NFPA Glossary of terms (ed. 2013)]

Note to entry: Plenums are typically located above ceilings or below raised floors and they are the areas that contain heating, ventilating or air conditioning ducts. Products such as data and communications cables, associated cable management systems and sprinkler piping are also often contained in plenums.

3.10

profile

extruded plastic product, excluding film and sheet, having a characteristic constant cross-section along the axis of the product

[SOURCE: ISO 472:2013, definition 2.839]

3.11

PVC-C

polyvinylchloride, which is a thermoplastic obtained by polymerization of vinyl chloride and to which additional chloride is chemically bonded by substitution of hydrogen atoms.

Note to entry: common names are chlorinated PVC and CPVC

3.12

PVC-P

polyvinylchloride (plasticized), which is a thermoplastic obtained by polymerization of vinyl chloride and plasticized by the addition of specific additives

Note to entry: common names are plasticized PVC, flexible PVC and soft PVC

3.13

PVC-U

polyvinylchloride (unplasticized), which is a thermoplastic obtained by polymerization of vinyl chloride

Note to entry: common names are unplasticized PVC and rigid PVC

3.14

spontaneous-ignition temperature

minimum temperature at which ignition is obtained by heating, under specified test conditions, in the absence of any flame ignition source

Note to entry: Spontaneous ignition temperature is typically used in fire tests while auto-ignition temperature is often used as a material or product property.

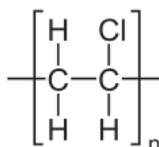
4 PVC building materials and products

4.1 Definition and description

4.1.1 General

PVC is the most widely used polymer in building and construction applications and, for instance, up to 70 per cent of World's annual PVC production is used in this sector.

PVC is a thermoplastic composed of 56,8 mass % of chlorine (typically derived from industrial grade salt) and 43,2 mass % of carbon and hydrogen (derived predominantly from oil or gas via ethylene). The chlorine content gives excellent intrinsic fire performance to PVC.



PVC resin is often supplied in powder form and long-term storage is possible since the material is resistant to oxidation and degradation. Various additives such as processing agents, stabilisers, fillers, plasticizers, flame retardants, and pigments are added to the PVC resin during the compounding stage, depending on the desired properties of the final product. The compound is then converted into PVC products.

According to ISO 1043-1, PVC belongs to Group A, homopolymers. PVC compounds are classified in different categories:

- PVC-U: unplasticized PVC, commonly named rigid PVC
- PVC-P: plasticized PVC, also named soft or flexible PVC
- PVC-C: chlorinated PVC, also identified as CPVC

ISO 11469 specifies a system of uniform marking of products that have been fabricated from plastics materials. It refers to ISO 1043-1 (basic polymers), ISO 1043-2 (fillers and reinforcing materials), ISO 1043-3 (plasticizers) and ISO 1043-4 (flame retardants).

NOTE: ISO 11469 is not intended to supplant, replace or in any way interfere with the requirements for labelling specified in products standards or legislation.

The same rules apply in case of PVC containing e.g. a plasticizer and/or a flame retardant (see clauses 4.1.2 to 4.1.5).

NOTE: When possible and appropriate, compounds containing plasticizers can be marked with the abbreviated term for the polymer followed by a hyphen, then the symbol "P" followed by the abbreviated term of the plasticizer in parentheses, as given in ISO 1043-3. The exact marking is generally specified in the product standard. It may be compulsory in case it is specified e.g. in an applicable regulation.

Whilst the marking system is intended to help identify plastics products for subsequent decisions concerning handling, waste recovery or disposal, it is also very useful to identify *a minima* a material to be subjected to fire testing.

NOTE: For characteristics other than the chemical composition of the material or product, such as reaction to fire properties, a complementary and specific marking can be used.

4.1.2 PVC-U based products

Unplasticized (also known as rigid) PVC products are intended for applications where rigidity is needed. Some common applications for PVC-U products include pipes, window profiles, conduit, siding, fences, decks and railings. The use of plasticizers differentiates flexible vinyl products from rigid ones. The rigidity of PVC is maintained by not introducing plasticizers.

In reaction to fire tests, PVC-U displays a high resistance to ignition, a low rate of heat release, and self-extinguishes when the external ignition source is removed. This is because of its high content of chlorine.

4.1.3 PVC-P based products

PVC is plasticized for applications where the flexibility of the final product is essential such as wire sheathing and insulation, floor and wall coverings and flexible sheets.

The fire properties of PVC generally deteriorate to a certain extent when PVC is plasticized depending on the amount and kind of plasticizer and other additives used. However, many of the plasticized PVC products in use will not continue to burn once the flame source is removed, even if not additionally fire-retarded. Moreover, technologies were developed in the 1980s and 1990s, using combinations of plasticizers and other additives, which resulted in plasticized PVC materials with fire properties similar or better than those of the corresponding native unplasticized PVC.

4.1.4 PVC-C based products

PVC-C is obtained from normal PVC resin to which additional chlorine is introduced in the polymer chain, to reach a chlorine content in the range of 62 to 68% by mass, leading to a different family of vinyl polymers. This addition leads to improved fire properties: further decrease in the flammability (including heat release) of the polymer and significant decrease in intrinsic smoke generation. The reason for this effect on smoke generation is likely to be a change in the mechanism of dehydrochlorination.

4.1.5 Flame retardants

The term "Flame retardant" refers to a range of additives of various chemical compositions that can be added to materials to improve their fire behaviour and reduce fire hazard. Various species of flame retardants, including smoke suppressants, alone or in combination, can lead to consistent lowering of heat release, flame spread, ignitability, (by increasing the time to ignition or the minimum heat flux for ignition), or smoke release.

NOTE: The presence of flame retardants is indicated according to ISO 1043-4.

Altogether there are over 200 different types of substances that can be used as flame retardants and they are often applied in synergistic combinations with each other. Not all flame retardants provide their functionality for all materials and some are often specific to or incompatible with certain materials. Properties depend on their physical form and use conditions.

A wide range of flame retardants are used with PVC construction products. Flame retardants can act in the condensed phase or in the vapor phase and they may even act in a combination of both. Typical flame retardants for PVC include those based on metal hydroxides (e.g. aluminium hydroxide or magnesium hydroxide), antimony oxide, zinc derivatives (e.g. zinc borate, zinc stannate or zinc hydroxystannate), bromine derivatives (e.g. brominated phthalates), molybdenum compounds, or phosphates (particularly aryl phosphates, aryl alkyl phosphates or halogenated phosphates), and a variety of other additives, often in various combinations.

Smoke suppressants are flame retardants used in PVC compounds to lower the resulting smoke production. Just like other flame retardants, smoke suppressants can act in the solid phase (i.e. the PVC matrix) or in the vapor phase, in each case in a physical or chemical manner.

The following discusses the mechanism of action of some flame retardants and/or smoke suppressants.

- Halogen-containing materials (mainly bromine and chlorine) tend to act primarily in the vapor phase as free radical scavengers. Some of the additives used are chlorinated paraffins, or polycyclic chlorinated or brominated materials.
- Aluminium trihydrate (or aluminium hydroxide, ATH) ($\text{Al}(\text{OH})_3$) and magnesium hydroxide ($\text{Mg}(\text{OH})_2$) act primarily by releasing water into the vapor phase and thus both cooling the vapor phase and diluting it to decrease the likelihood of reaching the flammability limit. They typically need to be used in high loadings.
- Antimony oxide (Sb_2O_3) typically needs the presence of halogen-containing materials for action, primarily in the vapor phase, by forming antimony-halogen compounds, so that it is a very effective flame retardant for PVC
- Zinc borate ($\text{Zn}_x\text{B}_y\text{O}_z \cdot n\text{H}_2\text{O}$) is a potential partial replacement for antimony oxide, and it is a char promoter which typically needs the presence of halogen atoms. In some cases, it can be synergistic with ATH.

- Aryl phosphates (especially aryl alkyl phosphates) are flame retardants and plasticizers and work to decrease both heat release and smoke release and they are often used in high performance PVC cable materials.
- Molybdenum compounds (molybdenum trioxide (MoO_3) and ammonium molybdate ($(\text{NH}_4)_2\text{MoO}_4$), also often used as a hydrate) act primarily as smoke suppressants by reducing the formation of aromatic compounds, which are soot precursors.
- Compounds of tin and zinc, especially zinc stannate (ZnSnO_3) and zinc hydroxystannate ($\text{ZnSn}(\text{OH})_6$) are, just like molybdenum compounds, primarily used to decrease smoke, as synergists, in high performance cable compounds.
- Some iron-based components generate a char layer after reacting with hydrogen chloride to produce iron (III) chloride (FeCl_3)
- Calcium carbonate (CaCO_3) and magnesium carbonate (MgCO_3) both act primarily as absorbers of hydrogen chloride and tend to reduce hydrogen chloride release and also smoke production

The type and levels of flame retardant (or smoke suppressant) additives used are dependent on the specific fire classification (such as a fire test) the material will need to meet.

PVC products, particularly unplasticized ones, have inherently good resistance to burning and the incorporation of flame retardants into PVC based rigid construction products is generally limited to particular applications in public buildings and certain indoor locations, to which specific regulations apply. However, the use of flame retardants and/or smoke suppressants is very frequent for electrical and/or optical fibre cables, construction products which, when they use PVC materials, involve plasticized PVC.

4.2 Product standards

A number of PVC products are covered by various standardisation committees. ISO and IEC technical committees (as well as ones from CEN and CENELEC and technical committees in individual countries) exist that have within their scope the properties of most PVC materials and products used in construction. The list below presents information on some committees that address the PVC products to which this Technical Report applies:

- PVC materials (including recycled and composite PVC materials)
 - ISO TC 61 SC9 WG20: Plastics - Thermoplastic materials - Poly(vinyl chloride)
 - CEN TC 249 WG11: Plastics - Plastics recycling
 - CEN TC 249 WG13: Plastics - Wood Plastics Composites (WPC)
 - ASTM D20 (Section D20.15.07) - Plastics - Thermoplastic Materials - Vinyl chloride polymers
- Plastics pipes and fittings:

- ISO TC 138: Plastics pipes, fittings and valves for the transport of fluids
- CEN TC 155: Plastics piping systems and ducting systems
- ASTM F17 (F17.25) Plastic Piping Systems (Vinyl Based Pipe)
- Profiles for doors and windows:
 - ISO TC 162: Doors and windows
 - CEN TC 33: Doors, windows, shutters, building hardware and curtain walling
 - CEN TC 249 WG21: Plastics - Profiles for windows and doors
 - ASTM D20 (D20.24) Plastics (Plastic Building Products)
- Covering sheets:
 - ISO TC 219 WG2: Floor coverings - Resilient floor coverings
 - CEN TC 99: Wall coverings
 - CEN TC 134 WG7: Resilient, textile and laminate floor coverings - Resilient floor coverings
 - CEN TC 249 WG22: Plastics - Wall covering panels for building applications
 - ASTM F15 (F15.15) Consumer Products (Wallcoverings)
- Flexible sheets (including stretched sheets)
 - ISO TC 61 SC11 WG3: Plastics - Products - Plastics films and sheeting
 - CEN TC 254 SC2: Flexible sheets for waterproofing - Synthetic sheets
 - CEN TC 357: Stretched ceilings
 - ASTM D20 (D20.19) Plastics (Film, sheeting and moulding products)
- Rigid sheets and profiles:
 - ISO TC 61 SC11: Plastics - Products
 - CEN TC 128 SC9: Roof covering products for discontinuous laying and products for wall cladding - Prefabricated accessories for roofing
 - CEN TC 128 SC10: Roof covering products for discontinuous laying and products for wall cladding - Gutters

- CEN TC 249 WG5: Plastics - Thermoplastic profiles for building applications
- CEN TC 249 WG12 - Plastics - Plastics jacketing
- Technical and composites products:
 - ISO TC 61 SC11 WG11: Plastics - Products - Wood-Plastic composites
 - CEN TC 88: Thermal insulating materials and products
 - CEN TC 217: Surfaces for sport areas
 - ASTM D20 (D20.20) Plastics (Plastic lumber)
 - ASTM D7 (D7.02.07) Wood (Wood/plastic composites)
- Electro-technical products:
 - IEC TC 15 - Solid electrical insulating materials
 - IEC TC 20: Electric cables
 - IEC TC 23: Electrical accessories
 - CLC TC 20: Electric cables
 - CLC TC 213: Cable management systems
 - ASTM D9 (Electrical and electronic insulating materials)

The standards and other documents issued by these committees generally address a panel of characteristics, properties or performance applicable to the concerned products to be used, both generally and in specific conditions, such as chemical, mechanical, dimensional and durability properties. However, safety related performance, including those related to fire safety, is addressed in a limited number of cases. Such performance is typically addressed in codes and regulations, which often use specific fire test methods.

The products related standards, technical specifications or technical reports often refer to ISO (and other) test method standards in order to complete the technical content applicable to the concerned products by linking characterisation or specification with test methods normative references.

Many of the recommended fire test methods applicable to PVC products are produced by ISO TC 61 and ISO TC 92. Other fire test methods are produced by IEC TC89 and IEC TC15. In the US, ASTM and NFPA also generate fire test methods. Geometry, mounting and fixing of specimens submitted to testing are often detailed in the corresponding product standards developed by the responsible product technical committees.

5 Fire safety strategy

5.1 Fire safety objectives

5.1.1 General

Fire safety objectives are best achieved by the application of fire safety engineering principles.

This chapter on fire safety objective is based on information provided by scientific studies and other standards, as shown below. ISO 23932 introduces general principles regarding fire safety engineering. It provides an operational, performance-based methodology for users to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineering approach based on the quantification of the behaviour of fire and people and based on knowledge of the consequences of such behaviour on life safety, property and the environment.

The present technical report is intended to be useful for developers, manufacturers and users of construction products because it lists the basic principles of fire safety design that should be applied to all generic phenomena associated with fire (e.g., fire growth, extent of smoke movement, structural behaviour) and the fire safety objectives addressing these phenomena, such as:

- the safety of life, including safe escape and safety of rescue teams
- the conservation of property, including avoiding propagation to adjacent buildings
- continuity of business operations
- protection of the environment
- preservation of heritage

The fire performance of a construction product should always be considered as an essential element in the context of the fire safety objective(s) defined for the situation envisaged. This technical report presents all the key parameters that should be considered to assess fire safety in any fire scenario, including: ignitability, ease of extinction, heat release, flame propagation, smoke obscuration, smoke toxicity, emergency measures and active fire protection measures. The optimization of a partial set of parameters would not be appropriate for defining a responsible fire safety strategy.

In terms of fire safety objectives related to user needs or social expectations, ISO 19208 lists the following commonly encountered subject matter of objectives:

- Hazards of outbreak of fire and of spread of fire
- Physiological effects of smoke and heat
- Alarm time (detection and alarm systems)
- Evacuation time (escape routes)

- Survival time (fire compartmentation)

ISO 15928-4 sets out a method for describing the fire safety performance within houses. It covers user needs, provides performance descriptions, and outlines evaluation processes. It includes the description of relevant parameters for early warning, fire suppression, fire containment, means of escape, control of structural behaviour and emission and spread of fire effluent. It is intended for use in the evaluation of the design and construction of houses, in the international trading of house sub-systems, and in developing tools to manage fire hazard and fire risk for the protection of buildings. It does not specify a level of performance and it is not intended to provide either some design method and/or criteria.

NOTE: Useful guidance and overviews of fire safety engineering as applicable to electrotechnical products are given in IEC 60695-1-12.

5.1.2 Safety of life

The objectives for a goal of minimizing loss of life or damage to health will typically be stated in terms of goals to ensure safe evacuation or rescue for occupants in all compartments in the built environment. For safety from injuries that can occur before an occupant can reasonably react to fire and begin evacuation, the objectives will typically be stated in terms of goals on equipment or other products to reduce the likelihood of fire occurrence. (See ISO 23932)

Incapacitation is reached when a threshold is attained with reference to any of the following parameters:

- heat (in case of radiation on the body and breathing hot air): discomfort occurs at 54°C, effects become dangerous at 65°C and are deadly above that temperature; humid air being more dangerous than dry air
- obstruction of the respiratory tract: accumulation of soot of all sizes, from nanoparticles to aggregates
- toxicity of the fire effluent, as a result of either asphyxiation or irritation
- smoke opacity, causing impairment of visibility and potential disorientation

Synergistic or antagonistic effects could occur depending on the composition of the smoke and the nature of the local environment.

NOTE: The ocular irritation produced by high levels of acidic or basic substances may be a cause of loss of visibility in addition to the physical one generated by the smoke itself. This phenomenon depends on the overall composition of the fire effluent and not only on any one specific substance.

5.1.3 Conservation of property

Property conservation objectives will typically seek to reduce or avoid both damage to the built environment and damage to contents, such as equipment. (See ISO 23932)

These objectives could be considered as relating to three types of situations. The first one relates to the place where the fire occurred, while the second one relates to adjacent locations, meaning

compartments or rooms away from the compartment of fire origin, to which the products of the fire (such as flames, heat, smoke and combustion products) can penetrate. The third area relates to locations so far away from the compartment of fire origin that heat effects can be ignored.

In the compartment of fire origin, the effects are primarily caused by heat released during the first phases of the fire, because the time scale is often too short for other chemical reactions to develop. Later in the fire, if the fire becomes big enough and reaches flashover, there will be complete property destruction. Once that stage has been reached, the chemical impact of any substance, including acidic chemicals released by halogenated plastics, is irrelevant.

In locations outside the compartment of fire origin but where heat effects are important, the level of property damage is heavily affected primarily by the heat release rate and total heat released by the fire.

In locations that are far away from the fire, where thermal effects can be ignored, only fire effluents would be relevant, and two types of damage should be considered:

- the deposition of soot, which is a typical consequence in building fires
- the corrosion by acidic substances, which is often very difficult to quantify because it very much depends on the materials exposed to the smoke and their respective surfaces. It should also be mentioned that many construction surfaces trap acidic species such as HCl (via decay of HCl), the consequence of which is a decrease of the level of acid in the atmosphere/gas phase as a result of losses on walls.

5.1.4 Continuity of business or service operations

The objective of business or operations continuity will typically seek to reduce the length of time that operations are interrupted but can also be stated in terms of the economic value of such interruptions, including market share and employment opportunities. (See ISO 23932)

This generally includes continuity of electrotechnical device operations, such as lighting, pumping, ventilation, alarm systems and computer systems, as well as human activities.

Continuity of essential human activities to maintain the minimum business operations defined in internal procedures need to be balanced considering safety of life. This aspect needs to be considered in industrial situations, often in retail and other commercial environments but it is less critical in the case of offices and private locations.

Consideration of the continuity of electrical and electrotechnical devices operations, both bridging by soot deposition and acidic corrosion of metallic/conductive parts need to be considered in those cases where heat effects can be ignored.

Short-circuiting of exposed electrical parts is a fast effect that occurs as soon as conductive components are exposed to soot deposition or humid smoke (burning any kind of organic material generates water to some extent). The acidic character of the smoke is of little importance; it is a matter of conductivity.

NOTE: the water used for extinguishment during fire-fighter operation could, in some cases, have as much impact on exposed electrical components as the smoke generated during the fire.

Corrosion of electrotechnical components is a phenomenon that needs to be considered in terms of medium to long-term continuity of operations or recovery of operations. Very often, critical components are simply replaced (sometimes by newer and better performing versions of the discarded articles) as a precautionary measure because it is often not known to what extent these articles have suffered from the effects of heat or of corrosive gases.

NOTE: General guidance on corrosivity is given in ISO 11907-1. Guidance on corrosivity with respect to electrotechnical products is given in IEC 60695-5-1. IEC 60695-5-2 addresses the relevance of test methods.

5.1.5 Protection of the environment

The environmental protection objectives will typically seek to reduce or avoid the immediate and long-term effects of a fire on the quality of the natural environment. If environmental quality needs exist, it is possible to state environmental protection objectives in terms of compliance with those needs. (See ISO 23932)

This objective relates to the outdoor (natural) environment. In this case only the impact of the smoke composition needs to be addressed and only large fires are likely to have an impact on the non-immediate environment such as fires in storage sites. It can be caused by:

- deposition of smoke particles containing harmful substances produced by the combustion of materials (e.g. polyaromatic hydrocarbons [PAH]) or the release of substances contained in the burning materials (e.g. heavy metals).
- aquatic pollution by the water run-off that can contain the same kind of substances as mentioned above.

In both cases, the presence of chlorinated substances such as dioxins is possible when burning materials contain chlorine. However, the production of dioxins depends on the fire conditions and does not constitute a significant threat to the environment, in particular at the scale of a building fire. Several studies suggest that the levels of dioxins are several orders of magnitude lower than those of PAH, which are carcinogenic halogen free residues that can be produced by a large range of burning materials.

5.1.6 Preservation of heritage

Heritage protection objectives will typically seek to avoid the loss or alteration of objects for which the value at stake is not primarily economic. These irreplaceable objects will typically be both old and unique, having cultural or other symbolic significance. (See ISO 23932)

The objectives in this area are broader than simply the resistance to destruction by fire: they also include mechanical stability, resistance to humidity and fungi, resistance to inappropriate behaviour of users or visitors, arson, and so on. Specific measures may be taken on a voluntary or regulatory basis. In terms of fire safety, specifications may refer to the use of particular designated materials. Clearly, the most important technique for passive fire protection is the use of non-combustible materials (something often not practical) or, at least, the use of low heat release materials. Examples of documents that handle such types of buildings are NFPA 909 and NFPA 914.

In these particular cases, active fire protection measures are used, the primary objective of which is the detection of any fire occurrence, followed by rapid reaction by dedicated personnel (trained people at first and fire brigades soon after). Other active fire protection includes fire suppression techniques (such as automatic sprinklers) which lead to the avoidance of the fire propagation and extinguishment. Other techniques include compartmentation (e.g. self-closing high fire resistance doors).

Based on these fire safety objectives, the focus is the immediate containment and extinguishment of the fire and the toxic potency of smoke is generally not critical.

5.2 Fire scenario

The number of possible fire scenarios in any built environment can be very large and it is not possible to quantify them all. The characterization of a fire scenario involves a description of fire initiation, the growth phase, the fully developed phase and extinction together with likely smoke and fire spread routes. This includes the interaction with the proposed fire-protection features for the built environment. Furthermore, it is necessary to consider the possible consequences of each fire scenario.

In order to assess the development and consequences of a likely fire in given situations by means of a fire safety engineering approach, a design fire scenario is to be selected that is tailored to the fire-safety design objectives and accounts for the likelihood and consequences of potential scenarios.

There can be several fire safety objectives being addressed including life safety, property protection, continuity of operations, environmental protection and preservation of heritage. A different set of design fire scenarios can be recommended to assess the adequacy of a proposed design for each objective.

ISO 16733-1 describes a methodology for the selection of design fire scenarios and design fires that are credible but conservative for use in deterministic fire safety engineering analyses of any built environment.

The selection of design fire scenarios is tailored to the fire-safety design objectives, and accounts for the likelihood and consequences of potential scenarios. The selection of design fires is also tailored to the fire-safety objectives and to ensuring credible but severe fire exposure conditions.

ISO 16733-1 also offers an exhaustive list of the characteristics of fire scenario. It says that each fire scenario is represented by a unique occurrence of events and circumstances as well as a particular set of circumstances associated with the fire-safety measures. The latter are defined by the fire safety design, while the former is what should be specified to characterize the scenario. Accordingly, a fire scenario represents a particular combination of events and circumstances associated with non-design factors such as the following:

- type of fire (smouldering, localized, post-flashover...);
- internal ventilation conditions;
- external environmental conditions;

- status of each of the fire safety measures, including active systems and passive features;
- type, size and location of ignition source;
- distribution and type of combustible materials;
- fire-load density;
- detection, alarm, and suppression of fire by non-automatic, human means;
- status of doors;
- breakage of windows, if not taken into account by the fire design calculation method.

Other factors that can be elements of some designs are treated as non-design factors if they are not considered choices for the design, such as the following:

- choices of contents and furnishings, structural materials and methods and interior and exterior finishes, affecting distribution and type of fuel or fire load density;
- automatic fire detection and alarm;
- fire suppression;
- self-closing doors or other discretionary elements of compartmentalization;
- building air-handling system or smoke-management system.

Other factors are always treated as elements of design, such as the following:

- performance of each of the fire-safety measures;
- reliability of each of the fire-safety measures.

Considering a defined fire scenario, it is recommended to review the following questions to better identify what would be the contribution of the product to the fire, and what would be the most appropriate route to mitigate the contribution or even to suppress it:

- would the outcome of the fire be the same if the product were not present?
- what is the product's role in the fire scenario?
- can the ignition of the product be controlled or prevented?
- is the product a significant source of heat release or flame propagation?
- is the effluent from the burning product a significant contributor to fire hazard?

- will other burning objects be major contributors to fire hazard?
- will the performance of the product need to be maintained during the fire?

6 Fire test methods - Description and relevance

6.1 General

6.1.1 Reaction to fire tests applicable to plastics construction products

In order to draft a fire test programme or simply to select the more relevant fire test(s) or in order to assess the validity of test results considering the intended purpose, it is recommended to take into consideration guidelines applicable to fire testing plastics materials and plastics products for use in construction.

ISO 10840 covers the following aspects of fire testing of plastics materials and products:

- selection of appropriate tests that reflect realistic end-use conditions;
- grouping of the reaction-to-fire characteristics that any given test or tests can measure;
- assessment of tests as to their relevance in areas such as material characterization, quality control, pre-selection, end-product testing, environmental profiling and DfE (Design for the Environment);
- definition of potential problems that may arise when plastics are tested in standard fire tests.

The flexibility of approach that is indicated with respect to the mounting and fixing of test specimens will be valuable when fire-testing laboratories and certification bodies are considering how to evaluate ranges of plastics that are used in different ways.

A list of reaction-to-fire fire tests from ISO TC92 for construction products is shown below. Other organizations, such as ISO TC61 (SC4, on burning behaviour of plastics) and IEC, CEN, CENELEC, ASTM and NFPA are standards development organizations that have developed relevant fire tests.

- ISO 1182, Reaction to fire tests for building products — Non-combustibility test
- ISO 1716, Reaction to fire tests for building products — Determination of the heat of combustion
- ISO 5657, Reaction to fire tests — Ignitability of building products using a radiant heat source
- ISO/TS 5658-1, Reaction to fire tests — Spread of flame — Part 1: Guidance on flame spread
- ISO 5658-2, Reaction to fire tests — Spread of flame — Part 2: Lateral spread on building and transport products in vertical configuration

- ISO 9239-1, Reaction to fire tests for floorings — Part 1: Determination of the burning behaviour using a radiant heat source
- ISO 9705-1, Fire tests — Full-scale room test for surface products
- ISO/TR 11925-1, Reaction to fire tests — Ignitability of building products subjected to direct impingement of flame — Part 1: Guidance on ignitability
- ISO 11925-2, Reaction to fire tests — Ignitability of building products subjected to direct impingement of flame — Part 2: Single-flame source test

6.1.2 Intermediate scale plastics reaction to fire tests

In view of the potential restrictions in the scaling-up of fire test results, it is advisable to run intermediate-scale fire tests, in particular when the design or the composition of the final product has the potential to impact the burning behaviour of the product.

ISO/TS 15791-2 provides a framework guide for the use of fire tests with intermediate specimen size typically between 0,25 m² and 1 m² applicable to semi-finished and finished products made of or containing plastics. It covers typical applications of such tests, as well as methods of preparation and mounting of the test specimen. The products suitable for this guidance are planar, linear or profiled products and can be tested in horizontal or vertical orientation. It defines the parameters measured, their value to the user of the test results and explains how they can be used for direct product assessment or as input data for scaling studies.

Other intermediate scale fire tests, for example EN 13823, are also available for use with plastics products.

6.1.3 Fire stage and fire tests

Since fire is a complex and scalable phenomenon, it is advisable to select a fire test particularly relevant for a specific fire stage in accordance with a defined fire safety strategy relative to a declared fire safety objective.

ISO/TS 3814 describes the relevance of, and how to apply, the reaction to fire tests developed by ISO/TC 92. Each reaction-to-fire test is related to the different phases of a developing fire in buildings and transport and has to be considered in relation to the fire scenario and the phase of the fire it represents.

ISO/TS 3814 is aimed at indicating those ISO tests which produce relevant and useful data for fire safety engineering and those which do not. It is also of use to regulators and to those who perform reaction-to-fire tests for various reasons, including manufacturers and those are responsible to create, control, and assess fire safety.

6.1.4 Assessment of the fire threat to people

In addition to the impact of heat and flame propagation, the impact of fire effluent in terms of smoke density and toxicity often needs to be assessed. It is recommended to follow guidelines for the assessment of the fire threat to people due to the complexity of the various fire parameters and

the environment where the fire occurs, including other fire safety measures taken independently of the materials and products chosen.

ISO 19706 is intended to serve as a general guide for the assessment of the fire threat to people. It encompasses the development, evaluation and use of relevant quantitative information for use in fire hazard and risk assessment. This information, generally obtained from fire-incidence investigation, fire statistics, real-scale fire tests and from physical fire models, is intended for use in conjunction with computational models for analysis of the initiation and development of fire, fire spread, smoke formation and movement, chemical species generation, transport and decay, and people movement, as well as fire detection and suppression. ISO 16732-1 provides general guidance for fire risk assessment and ISO 16732-2 provides an example (for an office building) of how to conduct such a risk assessment.

ISO 19706 is intended to facilitate addressing the consequences of a single, acute human exposure to fire effluent. It does not address other effects of the heat, gases and aerosols, such as effects on electronic equipment and effects of frequent, multiple environmental exposures of people, which are of importance in fire safety design.

ISO/TR 13571-2 describes examples of fire hazard assessment procedures that go beyond simply focusing on the smoke toxic potency of individual materials and considers broader fire scenarios.

In the electrotechnical field, IEC has published three useful general guidance standards. These are:

- IEC 60695-1-10, Fire hazard testing – Guidance for assessing the fire hazard of electrotechnical products – General guidelines.
- IEC 60695-1-11, Fire hazard testing – Guidance for assessing the fire hazard of electrotechnical products – Fire hazard assessment.
- IEC 60695-1-12, Fire hazard testing – Guidance for assessing the fire hazard of electrotechnical products – Fire safety engineering.

6.2 Relevance of results and studies comparisons

In discussions at a 2014 workshop on “Scaling of Toxic Gas Yields,” hosted by ISO TC92 SC3 (Fire Threat to People and the Environment), concerns were expressed that publications on scaling studies treat all test materials as identical if the generic designation is the same, even though they are potentially quite different. This concern pertains to:

- comparisons of test data at different scales and to comparisons among different studies using the same apparatus;
- series of tests within a single laboratory or among different laboratories;
- the use of published rankings of materials and products.

It affects the validation of the computational models used to simulate fire hazard and risk.

The problem arises because of the faulty assumption that all materials in a generic polymer group (e.g., PVC-U, PVC-P, PVC-C) are identical in fire performance to all other materials in the same

group. As is well known, polymers within a generic group are frequently modified or compounded to meet different specifications linked to the intended usage, only one of which is fire performance. Commercial products that contain multiple polymeric materials have an added degree of diversity and concern.

There are some cases in which this concern has been addressed, i.e., studies in which products and specimens from the same products were tested at different scales and inter-laboratory studies of test methods in which the test specimens were from common supplies. Furthermore, comparisons of the burning of pure polymers (e.g. PVC resin with similar molecular weight distribution, insignificant levels of additives, etc.) should show similar behaviour.

Adequate sample identification and as much as possible composition is the starting point for any scientific research. In the case of industrial products, this should include the manufacturer, product reference, lot number and any claimed performance classification. The supplier should be approached regarding the disclosure of additional technical data needed for the intended research.

The information that is central to defining similarity in the material or product to be tested in multiple laboratories and at different scales includes:

- chemical composition (element percentages, prevalence of functional groups; nature and level of additives, etc.),
- thermal properties (including density, thermal conductivity, and heat capacity),
- and documentation of the aging and conditioning of the specimens.

A series of standards developed by ISO TC 61 SC1 (Plastics - Terminology) provides guidance about the identification of plastics and standardized designations of materials (e.g., ISO 11469, Plastics - Generic identification and marking of plastics products). However, this system is intended to help identify plastic products for subsequent decisions concerning handling, waste recovery, or disposal and is not necessarily sufficient to characterize fire performance.

Relying on similarity of retail product names to establish similarity of fire behaviour is inadequate. Terms like "vinyl (flooring)" and "household electrical cable" encompass variations from brand to brand, country to country, etc. In such cases, it is incumbent upon the people doing the comparison to establish the needed degree of product similarity.

It would be worthwhile to explore the establishment of substantial and available supplies of materials and products for fire tests. This would enable comparisons among test series where the quality of agreement would only depend on such factors as the similarity of combustion conditions and the extent to which the specimens are representative of the whole combustible item, and not result from inherent differences in the test specimens.

In the absence of such a repository, comparison of gas yields (and perhaps other fire properties, such as ignition delay time, heat release rate, flame spread rate, etc.) is only proper and appropriate among studies (a) in which the test specimens are from a single, uniform batch or (b) if it is assured that any differences in composition do not affect the test outcome significantly.

7 Material fire characteristics relevant for PVC construction products

7.1 Combustibility

Common combustible materials typically contain carbon and hydrogen. The ultimate combustion product of carbon is carbon dioxide (CO₂), while that of hydrogen is water (H₂O). The heats of combustion of these two elements are high, 141,8 kJ/g for hydrogen and 32,8 kJ/g for carbon. Consequently, substances containing only carbon and hydrogen (hydrocarbons) have heats of combustion that are amongst the highest of all common combustible materials. Table 1 lists the gross heat of combustion of some common hydrocarbons.

Substance	Gross heat of combustion (kJ/g)
Methane (CH ₄)	55,5
Ethane (C ₂ H ₆)	51,9
Propane (C ₃ H ₈)	50,4
Butane (C ₄ H ₁₀)	49,5
Polyethylene	47,7
Gasoline	47
Kerosene	46
Paraffin Wax	46
Polypropylene	45,8
Polystyrene	43,7

Table 1: Gross heat of combustion of some common hydrocarbons

The presence of heteroatoms in the chemical structure of a material decreases the percentage of carbon and hydrogen, and therefore usually causes a decrease in the heat of combustion. Table 2 lists the gross heats of combustion of some polymeric materials that contain heteroatoms.

Substance	Gross heat of combustion (kJ/g)
Polyphenylene oxide	34,2
Polyacrylonitrile	32
Polyamide (Nylon) 6 or 6,6	30-32
Polycarbonate	31,3
Polyurethane	24-32
Poly (methyl methacrylate)	26,8
Polyethylene terephthalate	24,1
Wood	19-22
Paper	16-20
PVC (resin)	18,0
Cellulose	17,5
PVC-P (compound)	11-27
PVC-U (compound)	10-15
PVC-C (compound)	6-8
Polytetrafluoroethylene	6,7

Table 2: Gross heat of combustion of some common polymeric materials that contain heteroatoms

Pure PVC has a heat of combustion of 18,0 kJ/g. This value can be lowered or increased by the addition of additives and the heat of combustion of compounds of PVC can significantly deviate from that of the pure material.

Table 3 lists the most common combustion products of PVC. The five most common products from real fires are hydrogen chloride, carbonaceous char, water, carbon dioxide and carbon monoxide. When the combustion of organic materials is incomplete, intermediate chemicals, sometimes unstable in fire conditions, may be produced.

Name	Formula
Hydrogen chloride	HCl
Carbon (char)	C
Water	H ₂ O
Carbon dioxide	CO ₂
Carbon monoxide	CO
Benzene	C ₆ H ₆
Methane	CH ₄
Ethylene	C ₂ H ₄
Methanol	CH ₃ OH
Acetaldehyde	CH ₃ COH
Acrolein	CH ₃ CHCOH
Formaldehyde	HCOH
Formic acid	CHOOH

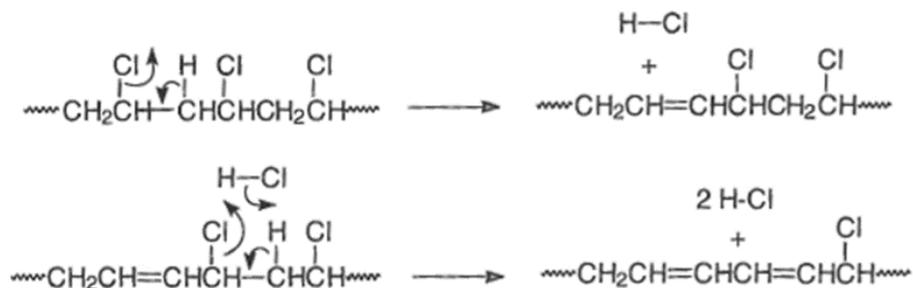
Table 3: Major PVC combustion products

Carbon monoxide is the penultimate species produced in the oxidation sequence shown above. It is known to be the most important toxicant produced in fire.

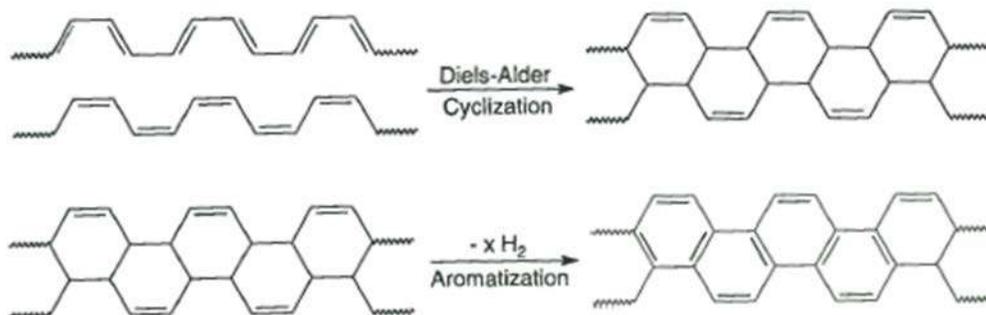
The relative amounts of these combustion products vary depending on the nature of the fire scenario and the exact composition of the PVC material involved. The approximate temperature of peak emission of hydrogen chloride (dehydrochlorination) starts at around 200°C, even before combustion occurs. Other species, principally non-chlorinated, will typically be released at higher temperatures over a broad range of temperatures, in fire situations, and this includes additives and their combustion products. Other combustion products containing chlorine are also potentially emitted at concentrations which depend on the combustion conditions.

A schematic pathway of PVC decomposition is shown below:

1st step: Autocatalytic dehydrochlorination process, which releases HCl:



2nd step: Cyclization and aromatization, leading to formation of char and release of non-chlorinated compounds.



3rd step: Oxidation of char, leading primarily to formation of CO and CO₂.

Table 4 lists some PVC combustion products other than hydrogen chloride and other than the products listed in Table 3 that have been observed under thermo-oxidative conditions, however in low concentration.

Name	Formula
Chlorobenzene	C ₆ H ₅ Cl
1,2-Dichloroethylene	C ₂ H ₂ Cl ₂
Dichlorobenzene	C ₆ H ₄ Cl ₂
Trichlorobenzene	C ₆ H ₃ Cl ₃
1,3-Dichloropropene	C ₃ H ₃ Cl ₂

Table 4: Examples of PVC combustion products containing carbon, hydrogen and chlorine

Some of the combustion products are unstable considering the combustion conditions, such as 1,2-dichloroethylene, and go to further decomposition, i.e. further oxidation of the carbon atoms (CO and CO₂) with the production of HCl.

NOTE: all figures given in tables 1 to 3 may be found in Handbooks of Chemistry.

7.2 Ignitability

7.2.1 Ignition temperature

PVC is among the materials that will not ignite unless the exposure temperature is relatively high. The resistance to ignition of PVC compounds depends however on their composition, essentially the presence and mass of organic and mineral additives such as plasticizers, fillers and flame retardants. Pigments have generally little to no impact on the ignition temperature. Ignition temperatures of some construction materials are listed in Table 5 [78, 79].

Material	Flash ignition temperature (°C)	Spontaneous ignition temperature (°C)
PTFE	~540	530
Polycarbonate	467	580
Polyamide (PA6)	421	424
PVC-P (FR)	400	>400
PVC-U	391	454
Polyester, glass fiber laminate	372	485
Polystyrene	352	492
ABS	349	466
Polystyrene foam (beadboard)	346	491
Polyethylene	343	349
PVC-P	330	>330
Polypropylene	320	350
Polyurethane, rigid foam	310	416
PMMA	290	456
Wood (Red oak)	260	416

Table 5 - ASTM D1929 ignition temperatures (°C)

NOTE: Guidance on ignitability of electrotechnical products is given in IEC 60695-1-20 and IEC 60695-1-21

7.2.2 Ignitability measured by the cone calorimeter test

Research has shown that ignition temperature is not an ideal means of assessing ignitability and that the ease of ignition is better assessed based on the time to ignition at a specific incident heat flux or by finding the heat flux necessary for ignition to occur. The parameters can be assessed by the cone calorimeter (ISO 5660 series). This is a sophisticated small-scale test that measures the effects of an incident heat flux, typically on a horizontal sample. There has been a significant amount of research indicating that information from the cone calorimeter is reasonably representative of real fire performance, especially in terms of heat release.

Tables 6 and 7 compare some results for PVC with those of other materials, regarding ignition times and heat flux values to cause ignition respectively. Both sets of data illustrate the good ignition resistance of PVC-U, PVC-C and PVC-P(FR).

Material		Heat flux		
		20 kW/m ²	40 kW/m ²	60 kW/m ²
PTFE	3mm sheet	No ignition	No ignition	252
PVC-P(FR)	Cable jacket plenum compound	No ignition	1253	424
PVC-C	Sheet compound	No ignition	621	372
PC	Polycarbonate sheet	6400	144	45
PVC-U	Extrusion grade	3591	85	48
PA6	Polyamide 6,6	1923	65	31
PET	Polyethylene terephthalate, bottle grade	718	116	42
PS	Polystyrene	417	97	50
PE	High density grade	403	159	47
Wood	Douglas fir board	254	34	12
ABS	ABS terpolymer	236	69	48
PP	Polypropylene	218	86	41
PMMA	Cardboard lined thick sheet (25mm)	176	36	11
PVC-P	Non-FR flexible cable compound	117	27	11
PU	Non-FR flexible polyurethane foam	12	1	1

Table 6: Cone calorimeter - ignition times (s) [80]

Material		Heat flux (kW/m ²)	
		600 s	100 s
PTFE	3mm sheet	63	83
PVC-P(FR)	Cable jacket plenum compound	60	110
PVC-C	Sheet compound	42	90
PC	Polycarbonate sheet	32	42
PVC-U	Extrusion grade	30	39
PA6	Polyamide 6,6	27	37
PET	Polyethylene terephthalate, bottle grade	22	42
PS	Polystyrene	15	40
PE	High density grade	≤15	50
PP	Polypropylene	≤15	37
ABS	ABS terpolymer	≤15	34
Wood	Douglas fir board	≤15	29
PMMA	Cardboard lined thick sheet (25mm)	≤15	27
PVC-P	Non-FR flexible cable compound	≤15	22
PU	Non-FR flexible polyurethane foam	≤15	≤15

Table 7: Cone calorimeter - Heat flux values to cause ignition (kW/m²) [80]

7.3 Oxygen index

The oxygen index test (ISO 4589-2) is a measure of the minimum concentration of oxygen in an oxygen/nitrogen mixture needed for sustained combustion under defined test conditions, which is an indication of the ease of extinction under specific experimental conditions. The higher the oxygen index the less likely it is that the material will continue burning. In fact, materials with high oxygen index (e.g. above 30) will tend to burn only when a source of flame and heat is present. They tend to extinguish otherwise, since normal atmospheres have about 21% oxygen, even less in O₂ depleted atmospheres, which are typical where fires occur and develop. It should be noted, however, that the oxygen index test is based on a low heat input and, thus, the results should not be extrapolated.

Note 1: Guidance on the oxygen index test is provided in ISO 4589-1.

Note 2: ISO 4589-3 describes a method for determining a flammability temperature, which is the minimum temperature at which the material exhibits sustained flaming combustion in air (i.e. 20.95% oxygen). The assessment is conducted over a range of temperatures typically between 40°C and 150°C, although temperatures up to 400°C can be used.

Oxygen index measurements are useful for R&D purposes and for quality control, but the values should not be used on their own to predict fire hazard. The oxygen index value of PVC materials is higher than those of many other common polymeric materials, which is a preliminary indication that they are less likely to continue burning if the source of heat is removed. Table 8 lists the oxygen index values of various materials used in building and construction.

Material	OI
PTFE	95,0
PVC-U	47,0
PVC-P (FR)	25 - 40
Polycarbonate	26,2
Polyamide (PA6)	25,1
Polyester, glass fiber laminate	21 - 43
PVC-P	21 - 36
Wood	21 - 22
PMMA	17,9
Polystyrene	17,7
ABS	17,6
Polyethylene	17,0
Polypropylene	17,1
Polyurethane, rigid foam	16,5

Table 8: Oxygen index (OI) values [80]

7.4 Heat release and heat release rate

7.4.1 General

Heat release and heat release rate are key properties regarding fire safety. The most important question to ask regarding the intensity of a fire is: "How big is the fire?" There is a single fire property that provides the answer to that question, namely the peak heat release rate. When a product is burning in a real fire, the fire will only spread to another product nearby if the burning product releases enough heat to ignite the other product. There is also a further consideration: a fire will not propagate unless the heat released by the first (burning) product is released sufficiently quickly so that it is not dissipated or lost while travelling through the atmosphere between the two products. Therefore, heat release rate dominates fire hazard and it has been shown that heat release rate is much more important than either ease of ignition, smoke toxicity, or flame spread in controlling time available for escape or rescue. The integral of the curve of heat release rate versus time is the total heat released.

Multiple mathematical models and equations have been developed to assess propensity for flashover from heat release rate data. A simple (rule of thumb) calculation can give an indication of the propensity for flashover in full-scale testing (ISO 9705) based on the ratio of ignitability data and heat release data obtained from the cone calorimeter (ISO 5660). The calculation is as follows:

$$\text{Flashover Propensity (or fire performance index)} = \text{TTI/Pk HRR}$$

where:

TTI = Time to ignition (in seconds), and

Pk HRR = Peak heat release rate (in kW/m²).

Heat release rate is associated with the effective heat of combustion, which is different from the gross heat of combustion. The effective heat of combustion is the amount of heat generated per unit mass lost by a material, product or assembly, when exposed to specific fire test conditions and it is typically assessed with heat release test methods. Therefore, the average effective heat of combustion over an entire test is a useful indication of fire performance. Rough assessments of heat release can be made based on measurements of mass loss (under the assumption that there is a constant effective heat of combustion). Mass loss calorimetry (such as those in ISO 13927 or ISO 17554) is used to assess mass loss continuously.

NOTE: Guidance on heat release is given in ISO/TS 5660-3 and IEC 60695-8-1. Guidance on flame spread is given in ISO/TS 5658-1 and IEC 60695-9-1.

7.4.2 Heat Release Data

Table 9 lists peak heat release rate values (PHRR) for a number of materials measured using the Ohio State University Calorimeter (OSU) using an incident heat flux of 20 kW/m²

NOTE: The OSU has been adopted as an ASTM standard (ASTM E906) and as a regulatory tool for the US Federal Aviation Administration (FAA).

Fire performance improves when the peak heat release rate is lower. The PVC materials all exhibit low PHRR values.

Material	PHRR (kW/m ²)
Polymethylmethacrylate (PMMA)	586,8
Polyethylene (PE)	476,9
Polypropylene (PP)	451,2
Hardboard	227,1
Polycarbonate (PC)	192,5
Plywood	113,6
Oak (25 mm)	79,5
Vinyl tile	75,7
ABS (FR)	70,7
FL PVC ¹	56,8
Gypsum board	47,3
PVC CIM ²	43
PVC EXT ³	40
LS PVC ⁴	39,3
PVC PL4 ⁵	17,5

Table 9 - PHRR values from OSU tests

with:

¹ FL PVC: Standard flexible PVC compound (non-commercial; similar to a cable compound) used for various sets of testing (contains PVC resin 100 phr; diisodecyl phthalate 65 phr; tribasic lead sulphate 5 phr; calcium carbonate 40 phr; stearic acid 0.25 phr)

² PVC CIM: PVC custom injection moulding compound with impact modifiers

³ PVC EXT: PVC rigid weatherable extrusion compound with minimal additives

⁴ LS PVC: PVC rigid sheet extrusion compound with smoke suppressants

⁵ PVC PL4: Semi flexible PVC thermoplastic elastomer alloy cable jacketing plenum compound, containing PVC and PVC-C

In the early 1980s, a improved small-scale test method was developed, to measure heat release rate: the cone calorimeter (ISO 5660, ASTM E1354). It can be used to assess ignitability but its primary function is to measure heat release, together with smoke release and mass loss.

Cone calorimeter test results have been shown to predict full scale fire test results for many products, including upholstered furniture, mattresses, electrical cables, wall linings and aircraft panels.

Table 10 lists peak heat release rates values and Fire Performance Index (FPI) values (see 7.4.1) for a number of materials measured using the cone calorimeter using an incident heat flux of 40 kW/m².

Material	PHRR (kW/m ²)	FPI (s.m ² /kW)
Polypropylene (PP)	1509	0,06
Polyethylene (PE)	1408	0,06
Polymethylmethacrylate (PMMA)	665	0,05
Polyethylene terephthalate (PET)	534	0,22
Polycarbonate (PC)	429	0,43
Douglas fir	221	0,15
PVC EXT	183	0,46
PVC CIM	175	0,42
LS PVC	111	1,65
PVC PL4	87	115
PVC-C	84	7,55

Table 10: PHRR and FPI values from the cone calorimeter tests

In the case of PHRR values, fire resistance increases with lower values whereas for FPI values it increases with higher values. The PVC materials, on both counts, behave well.

In 2007 ASTM D7309 was published. This is a test for the determination of flammability characteristics of plastics and other solid materials using microscale combustion calorimetry. The test method was originally developed by the Federal Aviation Authority in the USA. The test measures, among other parameters, the heat release capacity of materials, which is a fundamental property that is well correlated to the heat release rate. Table 11 lists heat release capacity (HRC) data for a variety of polymeric materials and shows that PVC exhibits excellent properties.

Material	HRC (J.g ⁻¹ .K ⁻¹)
Polyethylene (PE)	1450
Polypropylene (PP)	1106
Polystyrene (PS)	1088
Polycarbonate (PC)	578
Polymethylmethacrylate (PMMA)	480
Polyethylene terephthalate (PET)	366
PVC	157

Table 11 - HRC values from microcalorimeter tests

The heat release tests discussed above use small-scale samples of materials. In order to confirm that these test results are meaningful with respect to actual fire behaviour, it is often necessary to assess materials (or products) at a larger scale. A number of modern full-scale fire test methods have been developed for products, and they rely mainly on heat release rate measurements. They address wall lining products (via room-corner tests such as ISO 9705-1, NFPA 265 and NFPA 286), upholstered furniture, mattresses, stacking chairs, electrical cables, display stands and other decorative products.

Tables 12, 13 and 14 contain information from a study that compared the behaviour of seven wall-lining materials in a room corner test and in the cone calorimeter.

Table 12 shows the average heat release rates and the total heat release (THR) values measured in the room corner test. A 6,3 kg wood crib was used as the ignition source.

Material	Average HRR (kW)	THR (MJ)
Polycarbonate (PC)	135,6	133,9
Wood panel	73,2	85,2
FR ABS	54	70,2
FR acrylic panel	10,9	36,6
PVC-C	3	30,2
PVC-U	2,6	29,9
Low smoke PVC	0	25,6

Table 12: Room corner test data

Both parameters rank the materials in the same way with the PVC materials giving the lowest values. None of the PVC materials caused flashover.

Table 13 lists the cone calorimeter peak heat release rate data at four different incident heat flux (IHF) values. Table 14 lists the corresponding FPI values.

Material	PHRR (kW/m ²)			
	IHF=20 kW/m ²	IHF=25 kW/m ²	IHF=40 kW/m ²	IHF=70 kW/m ²
Polycarbonate (PC)	363	351	233	297
Wood panel	385	367	435	661
FR ABS	158	165	264	341
FR acrylic panel	62	124	109	183
PVC-C	17	42	54	94
PVC-U	109	105	224	270
Low smoke PVC	62	54	91	95

Table 13: PHRR values measured in the cone calorimeter

Material	FPI (s.m ² /kW)			
	IHF=20 kW/m ²	IHF=25 kW/m ²	IHF=40 kW/m ²	IHF=70 kW/m ²
Polycarbonate (PC)	5,97	2,83	0,34	0,09
Wood panel	0,72	0,37	0,09	0,03
FR ABS	4,37	0,47	0,14	0,04
FR acrylic panel	15,90	0,67	0,21	0,05
PVC-C	588,24	8,19	3,15	0,64
PVC-U	4,14	1,45	0,21	0,07
Low smoke PVC	60,03	18,87	0,54	0,13

Table 14: FPI values measured in the cone calorimeter

The best correlation is found for the IHF=25 kW.m⁻² values, but there are some anomalies, with the FPI value for polycarbonate being higher than expected and the FPI value for rigid PVC smaller than expected. However, all the PVC materials exhibited good fire resistance values in agreement with the large-scale test results.

7.5 Flame spread

7.5.1 General

The tendency of a material to spread a flame away from the fire source is a critical parameter to take into consideration in relation to the potential fire hazard and fire scenario.

A material can propagate the flame beyond the initial flaming zone. Flame propagation can occur in the horizontal orientation and then it is often referred to as “lateral flame spread”. Flame propagation can also occur in the vertical direction and that tends to be a more severe fire scenario. Unplasticized PVC is inherently resistant to flame spread because it tends to self-extinguish unless an external heat source is maintained.

NOTE: Many of the wire and cable fire tests assess vertical flame spread.

In some cases, the burning material can generate flaming debris or flaming droplets that can propagate fire by igniting another combustible material under or near the initial source. It is essential to distinguish flaming debris from flaming droplets. PVC materials tend to char and therefore very rarely produce flaming droplets.

NOTE: IEC 60659-9-1 gives useful guidance on flame spread, and IEC 60695-9-2 gives a summary and the relevance of flame spread tests for electrotechnical products.

ASTM E84 is a large-scale tunnel test widely used in North America for products and materials used in building applications. Classifications are based on a flame spread index (FSI) and a smoke index.

NOTE: the flame spread index is a non-dimensional number, which is placed on a relative scale in which asbestos-cement board has a value of 0, and red oak wood has 100.

Table 15 lists FSI values for a range of materials. The PVC materials all have low FSI values.

Material	FSI
ABS	200 - 275
Douglas fir/Cedar plywood	190 - 230
Acrylic plastic	220
Douglas fir	70 - 100
FR ABS	10 - 100
FR PC	10 - 65
PVC wall covering on gypsum board	10 - 25
PVC-U profile	15 - 20
PVC sheet (3 mm)	5 - 10

Table 15: FSI values from ASTM E84 tests [80]

NOTE: Other test apparatuses often used to assess flame spread include: IMO Fire Test Procedures Code Part 5 (equivalent to ISO 5658-2 and to ASTM E1317), ASTM E162 (radiant panel) and ASTM E1321 (Lateral Ignition and Flame Spread Test, or LIFT).

ASTM E162 (the Radiant Panel Flame Spread Apparatus) measures the surface flammability of building products by using a gas-fired radiant heat panel. The test result is Radiant Panel Index (RPI) that is determined from flame spread and heat evolution parameters. This index is required in various specifications especially for the mass transit industry (buses and trains) in North America.

NOTE: the radiant panel index is a non-dimensional number, which is placed on a relative scale in which highly flammable materials have high values.

Table 16 lists RPI values for a range of materials. The PVC materials all have low RPI values.

Material	RPI
Rigid PU foam	2220
Flexible PU foam	1490
FR Acrylic plastic	316
Plywood (Fir)	143
ABS	131
PC	88
FR PC	73
PVC-U	10
PVC-C	4

Table 16: RPI values from ASTM E162 tests [80]

7.5.2 Flame spread by flame propagation

The most severe fire performance specified for electrical cables is the one used in North America for cables intended for use in plenums. Multiple formulations exist that use PVC sheaths and even some formulations that use both PVC sheaths and PVC insulations; all of them need to meet the

NFPA 262 (or CSA FT6, in Canada) via the fire performance specified in the National Electrical Code. Note that the National Electrical Code (NEC, NFPA 70) regulates the fire performance specifications for electrical materials (especially cables) throughout the US.

Many PVC based surface products, such as PVC floorings and tiles and PVC based wallpapers and laminates, have been shown to pass the pass/fail criteria (as given in Table 17) for marine materials based on the test results of IMO FTP Part 5 or ISO 5658-2, which is however not specific to marine materials.

	Wall and ceiling surface	Floor covering
Critical flux at extinguishment (kW/m ²)	≥ 20,0	≥ 7,0
Heat for sustained burning (MJ/m ²)	≥ 1,5	≥ 0,25

Table 17: Pass criteria for flame propagation (IMO FTP Code, Part 5)

7.5.3 Flame spread by flaming droplets

Flame spread by flaming droplets is a material property (propensity to generate) that is relevant only in situations where the product is not horizontally laying down on a support (fire scenario).

ISO 9773 specifies a small-scale laboratory screening procedure for comparing the relative burning behaviour of vertically oriented thin and relatively flexible plastics specimens exposed to a low-energy-level flame ignition source. PVC materials will typically not produce flaming particles unless they have been heavily plasticized and have not been flame retarded. It is similar to the vertical version of UL 94 test. The classification ranges from V-0 (best) through V-1, V-2 and Burn (B, worst, meaning fail). Classifications of V-0 and V-1 do not allow flaming drops. PVC materials usually obtain a UL 94 V-0 rating down to the lowest thickness typically measured, usually 1 mm as shown in Table 18.

Material	V-0 @ 1 mm	V-0 @ 2 mm	V-0 @ 3 mm
PVC Cable FR1	V-0	V-0	V-0
PVC Cable FR2	V-0	V-0	V-0
PVC Cable FR3	V-0	V-0	V-0
PVC Cable FR4	V-0	V-0	V-0
PVC Cable Non FR	V-1	V-2	V-0
Chlorosulphonated PE	V-1	V-0	V-0
PTFE	V-0	V-0	V-0
LDPE Cable Non FR	B	B	B
EVA Cable FR1	B		
EPR Cable FR2	B		
EVA Cable FR3	V-1	V-0	V-0
EVA Cable FR4	B	B	B
EVA Cable FR5	V-0	V-0	V-0
Polyphenylene Oxide	B	B	B
EVA Cable FR6	B	B	V-0
PVC PL2	V-0	V-0	V-0

Table 18 – UL 94 V Test Results for Wire and Cable Materials [80]

7.6 Smoke generation

7.6.1 Smoke obscuration

Smoke obscuration is a serious concern in fires, because when visibility decreases it hinders both escape from the fire and rescue by safety personnel. A decrease in visibility is the result of a combination of several factors: e.g. how much material is burnt in the real fire, how much smoke is released per unit of material burnt, the volume into which the smoke is emitted, and the nature of ventilation. Just like the total heat released is the integral of the curve of heat release rate versus time, the total smoke released is the integral of the curve of smoke release rate versus time.

PVC decomposes thermally by dehydrochlorination (release of hydrogen chloride or HCl), with the formation of double bonds in the molecular structure of the remaining material and the formation of aromatic hydrocarbons. Further chemical reactions then lead to the formation of soot. Chlorine acts as an inhibitor of combustion reactions in the vapour phase and this tends to increase the formation of incomplete combustion products, including not just carbon monoxide but also carbon instead of carbon dioxide. For these reasons, it is commonly considered that PVC materials have intrinsically a potential for dense smoke release when reported on a per mass basis.

However, the decrease in visibility in an actual fire scenario is the result of a combination of two factors: how much material is burnt in the fire and how much smoke is released per unit material burnt. It is also a function of other scenario properties, such as the fire intensity and the oxygen supply.

One or several of the following can attenuate the impact of smoke on fire safety:

- the chemical nature of the basic material
- material additives such as flame retardants and smoke suppressants
- detection: warning/alarm systems, optical/heat detectors
- suppression: e.g. sprinkler systems
- building design: compartmentation and effective escape routes
- ventilation: automatic opening of smoke exhaust systems or forced ventilation

The colour of smoke and loss of visibility are not necessarily linked: a white smoke may cause a greater loss of visibility than a black smoke.

NOTE: Guidance about smoke measurement is given in IEC 60695-6-1. IEC 60695-6-2 gives a summary and the relevance of smoke tests for electrotechnical products.

As is the case for other fire parameters, smoke measurement is best evaluated in large scale tests. However, for practical reasons and for R&D purposes, many small-scale tests have been developed.

The cone calorimeter (ISO 5660) is a small-scale dynamic flow-through fire test, which can also be used to assess smoke obscuration.

Table 19 lists two smoke parameters for the materials listed in table 10:

- Total smoke release (TSR): total amount of smoke released during the test. It is a measure of the smoke producing potential of the test material when it is forced to burn.
- Smoke factor (SF): product of the total smoke released (TSR) and the peak heat release rate (PHRR). This is a parameter calculated by combining the smoke producing potential of the tested material with a measure of its resistance to burning. This gives a better measure of the smoke hazard of the material.

Material	PHRR (kW/m ²)	TSR	SF (MW/m ²)
Polypropylene (PP)	1509	2503	3777
Polyethylene (PE)	1408	1870	2633
Polymethylmethacrylate (PMMA)	665	3646	2424
Polyethylene terephthalate (PET)	534	2837	1515
Polycarbonate (PC)	429	3620	1553
Douglas fir	221	287	63
PVC EXT	183	7027	1286
PVC CIM	175	6653	1164
LS PVC	111	1937	215
PVC PL4	87	670	58
PVC-C	84	200	17

Table 19: Smoke data from the cone calorimeter tests (at IHF = 40 kW/m²) [80]

The smoke factor data show that PVC materials, when assessed properly, do not present a significantly greater smoke hazard than many other commonly used materials.

Studies of full scale room-corner tests (with materials lining walls of a real scale room) have shown that the majority of materials with low flame spread or low heat release, like PVC materials, tend to also exhibit low smoke release. In a series of studies only some 10% of the materials tested (8 out of 84) exhibited moderate or high heat release (or fire growth) characteristics together with high smoke release. This is an important consideration when assessing PVC materials in products that occupy large surfaces, because PVC materials have intrinsically high smoke release, but only when the entire material is forced to burn.

7.6.2 Smoke toxicity

Statistics show that the majority of fire fatalities principally result from the inhalation of smoke and combustion products, but that they occur from fires that have become so large that they have left the room of origin. Figure 1 is a graphical view of statistics generated by the NFPA in the USA, showing the numbers of fatalities due to smoke inhalation vs. burning and other causes. The data show a decreasing trend from the period between 1979 and 2005.

NOTE: The category "Both" has been introduced during the concerned period (no data available until 1998)

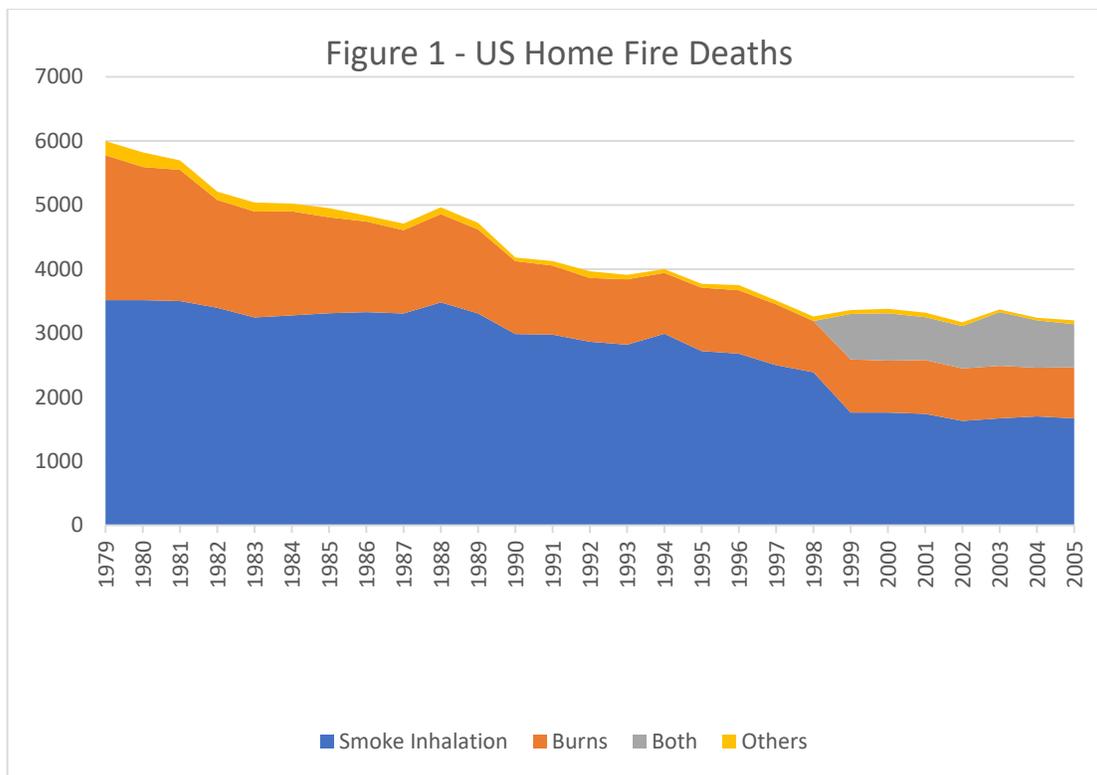


Figure 1: Fire fatalities (USA, between 1979 and 2005) [81]

The toxic effects of fire can be avoided or attenuated if the source fire remains small or develops slowly.

Carbon monoxide is known to be the most important toxicant produced in fire. CO is odourless and non-irritating. It is not detected by human senses (specific detectors are needed) despite the fact that it can be emitted at very high levels. In fact, flashover fires (which have oxygen-depleted atmospheres) typically contain about 20% of the mass burnt as carbon monoxide. Other gaseous products in fire effluents are detectable by odour. These include irritant chemicals, such as hydrogen chloride and acrolein. HCl, emitted from chlorine containing materials, is detectable at a very low level (approx. 3 µl/l), well below its LOC (Level of concern, several hundreds of µl/l).

Polyaromatic hydrocarbons (PAHs), including the highly carcinogenic benzo[a]-pyrene, are always produced in fires, at a level dependent on the fire conditions. These chemicals typically do not contain halogens and are often carcinogenic. They may be released in smoke and adsorbed on particles of soot that can be inhaled. They can pollute the site of the fire and the environment when transported by the water run-off from the water used in fighting the fire.

The combustion of chlorinated hydrocarbons and of any chlorine-containing materials generates hydrogen chloride and chloroaromatics, the amounts and chemical compositions of which depend on the fire conditions. Experience shows however that neither elemental chlorine (Cl₂) nor phosgene (Cl₂CO) have ever been found at any significant level in fire smoke [82]. Chlorinated dioxins and furans may be produced, but at a very low level, generally below the level of PAH, and not above the levels found in natural forest and wildland fires.

Chlorinated dioxins and furans can be produced from PVC compounds, but they are typically formed when PVC materials are thermally decomposed, or combusted, in specific conditions such as incinerators, particularly when operated at relatively low temperatures. However, studies have demonstrated that the amounts of dioxins generated from PVC in particular and other chlorine containing substances in dwelling fires are of no major toxic concern for human health and the environment in comparison with other toxicants, such as PAHs.

Vinyl chloride is the monomer used for the production of PVC and is not a concern in the context of fire safety because PVC does not thermally depolymerize forming monomers.

The quantification of the toxicity of fire effluents is not unequivocal, in particular for two major reasons:

- because fire is a dynamic phenomenon, the composition of the effluents (both in terms of substances evolved and concentrations) varies with time, e.g. in relation to the temperature and the oxygen availability in the atmosphere;
- the choice of criteria will depend on many variables, particularly the assumed fire scenario and the fire safety objectives.

ISO 13571(2012) contains guidelines addressing life-threatening components of fire by giving a methodology for estimating the time to compromised tenability in fires. It addresses the effects of asphyxiant and irritant toxicants as well the effects of heat and visual obscuration.

NOTE: Guidance on fire effluent toxicity for electrotechnical products is given in IEC 60695-7-1, IEC 60695-7-2 and IEC 60695-7-3.

In the absence of precise knowledge, it is possible to approximate the distribution of the individual susceptibilities by a log-normal distribution with a median value of 1 as the threshold for FED (fractional effective dose) and FEC (fractional effective concentration).

Table 20 gives the value of F of irritant gases. It is the volume fraction that is expected to seriously compromise occupants' tenability and it is used in the irritant-gas model of ISO 13571(2012). The lower the value, the more irritating is the gas.

Irritant gas	F ($\mu\text{l.l}^{-1}$)
HCl	1000
HBr	1000
HF	500
Formaldehyde	250
NO ₂	250
SO ₂	150
Acrolein	30

Table 20: F value for irritant gases from ISO 13571(2012)

ISO/TR 13571-2, Annex B, gives an example of application to real-scale fire scenarios (FED calculations for fire experiments conducted in a full-scale test of single sleeping rooms), based on a French study [83]. The fire scenarios are of particular interest because they incorporate a significant mass of PVC products.

The studied room is a small 9 m² room, equipped with finishes and furniture as in everyday life. The fuel mass load of PVC products is 34%, which is somewhat higher than average. Wooden products represent 54% and other products such as paper, PU foams, and other materials represent 12% of the total of combustible materials. Various scenarios of ignition source, origin and events such as door openings have been tested. The room was instrumented with a large number of sensors, in order to measure both physical and chemical parameters and to enable the calculation of tenability data.

Depending on the fire scenario, compromised tenability conditions are typically due to the action of the asphyxiant gases (carbon monoxide and hydrogen cyanide) or to thermal effects. Irritant gases, including hydrogen chloride, were a minor factor. In one scenario, less than 1 in 100 people are in compromised tenability conditions due to the action of irritating gases.

7.6.3 Smoke corrosivity

Corrosivity of smoke from fire is a well-recognised problem. It concerns the combined effects of corrosive gases and solid particulates on exposed metallic surfaces. It is more a property protection issue, in terms of functioning of machinery and electronic equipment, than a human threat. Deposition of soot is quicker than chemical corrosion and its effects occur more rapidly. On the other hand, corrosion rapidly develops once the environmental parameters are favourable, i.e. in the presence of reacting chemicals (acidic, basic or ionic) in a wet and hot atmosphere.

Metal corrosion can occur in two different ways:

- a) chemical reaction by corrosive gases dissolved in water on the surface
- b) deposition of hygroscopic particulates, which contain dissolved corrosive gases

Acidic corrosion of metallic structures is generally not to be considered in a fire scenario because of the thermal effects of the fire, which may impact those metallic structures more seriously and because corrosion is a relatively slow phenomenon compared to the time scale of a fire.

Soot deposition can impact electrotechnical equipment by bridging circuits. This can occur concomitantly with corrosive attack but there is no direct interdependence between the two phenomena.

Smoke from fire can be acidic if mineral acids (e.g. hydrogen chloride, hydrogen fluoride, hydrogen bromide) or organic acids (e.g. acetic acid, formic acid) are present. Corrosivity of acidic smoke can be assessed by direct methods that measure loss of metal on a target and by indirect methods using pH and conductivity measurements of a water extract from the smoke. However, a study of copper loss versus smoke acidity showed no correlation as shown in Figure 2.

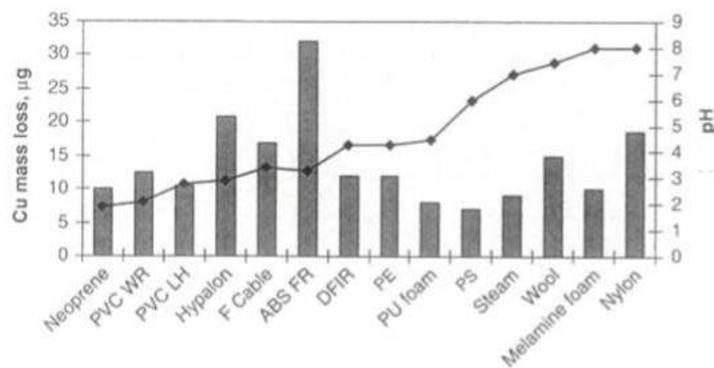


Figure 2: Corrosivity (mass loss of Cu; bar chart) vs. acidity of water extracts of smoke from various synthetic materials (pH of water extract; line chart) [84]

Fires involving PVC generate smoke with a more or less pronounced acidic character due to the presence of gaseous HCl. It can be trapped by water and starts corrosion of exposed metallic surfaces.

NOTE: the rate of corrosion also depends on the metal composition: e.g. CuNi alloy stainless steel, carbon steel or zinc do not behave equally, nor do printed circuits.

Considering construction products, the presence of HCl in smoke from burning articles containing PVC should be addressed in the context of closed environments where other materials, potentially capable of releasing other corrosive chemicals, can be found. Acidic species can also be neutralised by chemically reactive surfaces, such as matte paint, concrete or plasterboards.

NOTE: Guidance on the corrosivity of fire effluent on electrotechnical products is given in IEC 60695-5-1 and IEC 60695-5-2.

7.6.4 HCl decay

During the 1980s a series of 23 studies were conducted to investigate the persistence of HCl in a fire atmosphere [84]. These studies showed that HCl reacts very rapidly with most common construction surfaces (e.g. cement block, ceiling tile and gypsum board) and that, therefore, the peak HCl concentration found in a fire is much lower than would be predicted from the chlorine content of the burning PVC. Moreover, this HCl concentration soon decreases and HCl disappears almost completely from the fire atmosphere.

Figure 3 shows the HCl concentration-time pattern for several experiments where PVC cables (containing the chlorine equivalent of 8,700 µl/l of HCl) were electrically decomposed in the presence of sorptive surfaces typical of construction surfaces. In one case, with a simulated plenum, the peak HCl concentration found was only 10% of the theoretical (stoichiometric) value. A consequence of this HCl decay is that toxicity tests carried out in typical (non-sorptive) glass or plastic exposure chambers will overestimate the toxicity of PVC smoke, because HCl does not decay as fast as on construction surfaces, so that HCl is present longer than in real fires.

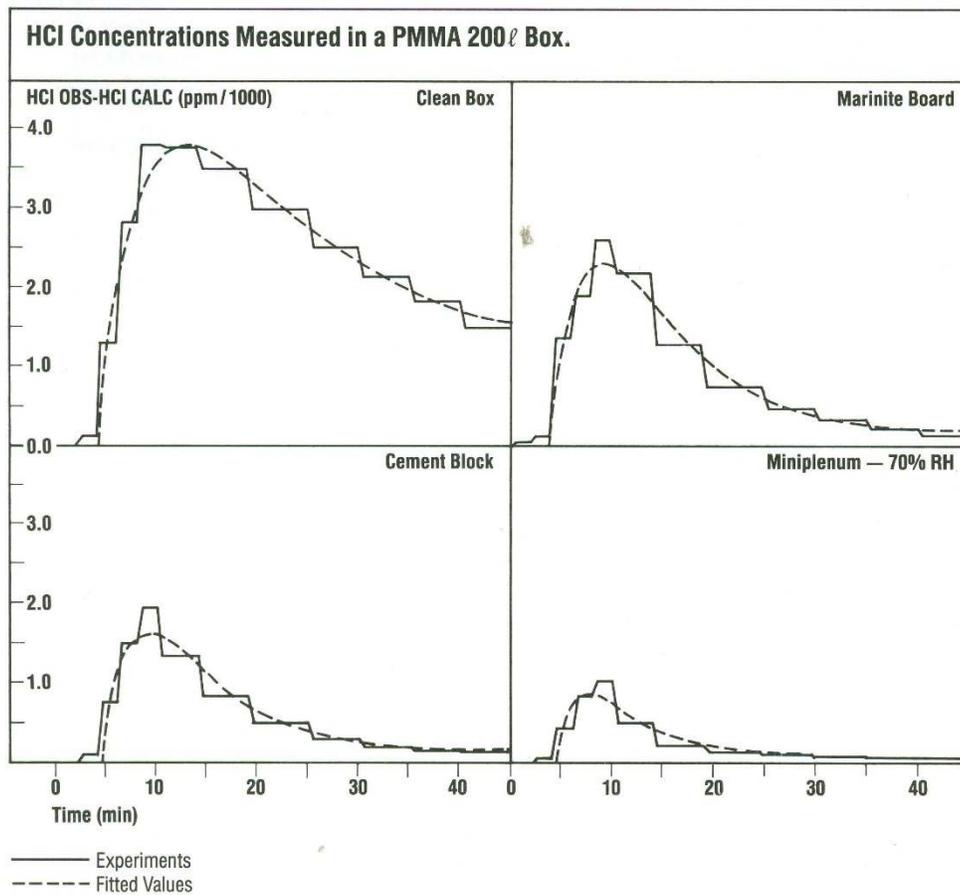


Figure 3: HCl From Thermal Decomposition of PVC Cables in a Lined PMMA Box [85]

Large-scale tests of burning and smouldering PVC floor coverings showed that about 50% of evolved HCl was deposited on the walls of the room [86]. The concentration of deposited HCl depends on the wall covering (Figure 4). As expected, porous wall coverings tend to absorb more HCl.

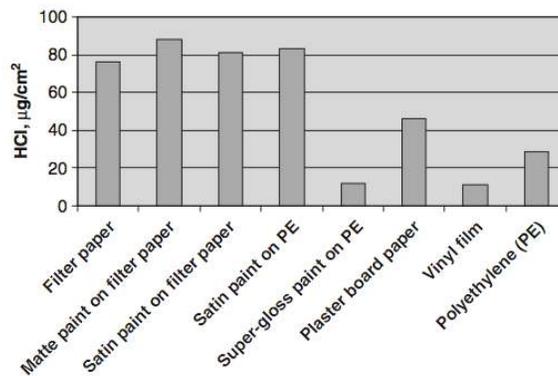
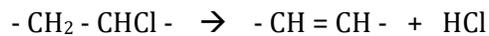


Figure 4: Concentration of deposited HCl on wall coverings [86]

In various situations, HCl released from burning PVC is unlikely to affect victims outside the room of fire origin (meaning that they won't affect victims in the post-flashover period). An example of such situations has been described by full-scale experiments in the US, conducted in a real plenum and in a long corridor, among others. The plenum tests showed that even if massive amounts of PVC are thermally decomposed in a plenum space above a room, no detectable amount of HCl is transferred down into the room below unless driven by an air conditioning system, while CO does accumulate in the room. Even when driven by the air conditioning system, the test suggested that measured HCl concentrations were found to have no toxicological concern.

7.7 Char formation and intumescence

PVC is an example of a charring material (in contrast to many other thermoplastic materials) that leaves much of the original carbon content as a solid residue, meaning that less of it can burn in the gas phase. The presence of chlorine in PVC exerts its influence in two ways: causing an increase in hydrogenated char formation (meaning that less flammable decomposition products are formed) and generating HCl, which then acts as a gas phase scavenger slowing down further reactions of flammable products in the gas phase.



The char formed can be a low-density material and has two positive effects regarding fire safety:

- it is a barrier between the source of heat and the unaffected polymer material leading to a reduction of its rate of decomposition;
- it reduces the release of flammable gas.

Intumescent chemicals that cause swelling up behind the char layer may be added to PVC to enhance its fire protection property. For example, this fire safety solution is used when the intent is to prevent fire spread between two compartments. PVC conduits and foamed PVC seals are available to comply with this situation thanks to additives that enhance the charring and intumescence properties of PVC.

NOTE: There is no ISO standard to refer to as concerning the testing of material intumescence. There is a French Quality Mark addressing intumescence properties of pipes and fittings, based on the expansion of material when exposed in the cone calorimeter (NF 513) [87]

Annex A (Informative)

Example of declaration of performance (DoP)

A.1. Example 1: PVC pipes

A plastics pipe complying with EN 15012 (Soil and waste discharge systems within the building structure - Performance characteristics for pipes, fittings and their joints), was submitted to fire tests in order to declare its fire performance with reference to the Directive 89/106/EEC (afterwards replaced by Regulation 305/2011, commonly referred to as the Construction Products Regulation [77]).

The product tested was a 3 mm thick, fire retarded PVC pipe for drainage of rainwater. The mounting and fixing of the test specimen was as defined in EN 16000.

Test results obtained from 3 specimens are given in Table A.1.

Test results according to EN 13823					
Parameter	Unit	Test 1	Test 2	Test 3	Mean value
FIGRA ¹ 0,2 MJ	W/s	47	63	51	54
FIGRA 0,4 MJ	W/s	47	63	51	54
THR600 ²	MJ	0,6	2,4	0,5	1,2
SMOGR ³	m ² /s ²	35	46	44	42
TSP600 ⁴	m ²	77	46	44	42
Flaming droplets ≤ 10s	Y/N	no	no	no	no
Flaming droplets > 10 s	Y/N	no	no	no	no
Test results according to EN ISO 11925-2					
Exposure time = 30 s	≤ 150 mm 60 s	Pass	Pass	Pass	Pass
Exposure time = 15 s	≤ 150 mm 20 s	Pass	Pass	Pass	Pass

Table A.1: Test results obtained in view of the declaration of the reaction to fire performance

¹ Fire growth rate

² Total heat release after 600 s

³ Smoke growth rate

⁴ Total smoke production after 600 s

The classification of the product was carried out in accordance with EN 13501-1:

- The product, in relation to its reaction to fire behaviour was classified "B"
- The additional classification in relation to smoke production was "s2"
- The additional classification in relation to flaming droplets was "d0"

Consequently, the reaction to fire classification and the marking of the product was declared

"B-s2, d0"

Annex B (Informative)

Example case history

B.1 Plastimet Accident

Hamilton, Ontario, Canada 9-12 July, 1997

A massive 4-day fire occurred at the Plastimet Inc. plastics recycling facility, in Hamilton, Ontario (Canada) in July 1997. The facility had a warehouse containing some 400 tonnes of PVC and other recyclable plastics.

By the time the firefighters arrived (within a few minutes) the building was engulfed in flames. The cause of the fire was arson by a young boy. In view of the concerns about health and environmental effects, the provincial Ontario government made a thorough investigation and issued a report, with the summary shown below, authored by Socha et al. [88].

“A compilation and interpretation of the environmental monitoring data regarding the fire at the Plastimet Inc. plastics recycling facility in Hamilton, Ontario was presented. The fire occurred in the early evening of July 9, 1997 and ended in the morning of July 12, 1997. Approximately 400 tonnes of polyvinyl chloride (PVC) and other plastics caught fire. Several hazardous substances were emitted directly to the air and indirectly to the water and land. These included hydrogen chloride, dioxins, benzene, PAHs and metals. Within days of the fire, the substances tested for had returned to concentrations within or close to normal urban background range for air, water, soil and vegetation.

According to public statements issued by the Hamilton-Wentworth Regional Health Department, no long-term human or environmental health effects are expected to occur as a result of the Plastimet fire.”

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