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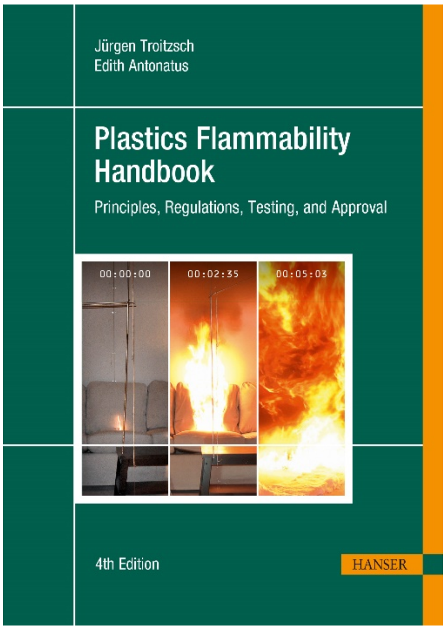

Sample Pages

Plastics Flammability Handbook

Jürgen Troitzsch and Edith Antonatus

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Preface to the Fourth Edition

In the past, none of the many publications on the reaction to fire of plastics provided a comprehensive review of the fundamentals, as well as of the relevant regulations and test methods. The *International Plastics Flammability Handbook* was first published in 1983 to fill this gap. However, in the 1980s, major changes occurred in the field of plastics fire behavior ratings on national and (increasingly) international levels. These changes made it necessary to prepare a completely revised 2nd edition of the handbook, which was published in 1990. The 1990s saw a breakthrough in the internationalization of fire testing and classification, particularly for products in buildings, electrotechnical applications, and transportation. At the same time, the perception of how to assess the main parameters governing a fire and the role of combustible materials like plastics was redefined, and led to new approaches particularly in the fields of heat release, smoke development, and toxicity of fire effluents. All these developments required a comprehensive revision and part-rewrite of the handbook, which was published in its 3rd edition in 2004.

Since then, many further changes have taken place in the fire performance requirements for construction products and rail vehicles in the European Union, the USA, and the Asia–Pacific region. In addition, the ongoing developments in the fields of electrical engineering and cables, and furniture and furnishings, as well as the ever-growing interest in smoke and toxicity of fire effluents, made it necessary to prepare a 4th edition of this handbook.

So, more than 15 years since the last edition, it was time to restructure and simplify the contents of the book, and to ask leading experts in the field to revise and to rewrite the various chapters. For this edition, Edith Antonatus agreed to join me as co-editor in order to make this major revision possible, and we want to express our gratitude to the over 30 co-authors whose expertise and commitment have made this project feasible.

The handbook consists of three parts.

Part I, “Fundamentals”, begins with an introduction to fire prevention, fires, and fire statistics, and continues with a description of the basic principles of the burning of plastics, the role of flame retardants, their mode of action, and their application to improve the fire safety of plastics. Chapters on the burning behavior of textiles and flame-retardant textiles, smoke development, and smoke suppression follow. In the 3rd edition of this handbook, the chapters on smoke development and toxicity of fire effluents were presented as Part III "Fire effluents" at the end of the book. In this edition, they have been moved to Part I, where, after the chapter on the basics of smoke formation, the chapters on smoke development and toxicity, as well as combustion toxicology of fire effluents, now jointly describe this increasingly important topic.

It is hoped that this will facilitate the reader's introduction to this complex subject, and also provide the background to better understand why the fire test procedures, regulations, and approval criteria covered in the second part of this handbook are necessary to provide adequate fire safety.

Part II, "National and International Fire Protection Regulations and Test Procedures", starts with a general introduction to fire regulations and codes, and the fire test methods needed to satisfy them, followed by a comprehensive overview of international fire safety standardization, with the work of the International Standards Organization (ISO), the European Committee for Standardization (CEN), and the international electrotechnical committees as examples.

The legal provisions regarding the fire performance of plastics and other combustible products form a large part of the book, and are arranged according to a consistent scheme for a selection of countries in the three major regions (North America, Europe, Asia–Pacific). The section on each country commences with an account of the statutory regulations, and continues with a summary of the relevant test methods in the form of diagrams and tables of test specifications. Officially recognized test institutions and procedures for obtaining official product approval are enumerated under the heading "Official Approval". Each section ends with a look at future developments in the relevant country. The reader is thus able to grasp the essentials at a glance. Further details can be taken from the original standards and regulatory documents listed in the bibliography at the end of each section.

The most extensive section of the handbook is devoted to the building sector, for which numerous fire safety regulations and test methods have been developed in all industrialized countries, and where a tremendous harmonization effort has virtually been completed in Europe. But even there, tests and classifications for specific building components such as the fire performance of façades and the external fire exposure of roofs are still not harmonized. To date, the toxicity of construction products is not part of the classification system developed by the European Commission, but subject to intense discussion. In other countries and regions of the world, particularly in Asia, great efforts have been made to improve existing smoke and toxicity regulations and test methods.

In the chapter on transportation (motor vehicles, rail vehicles, ships, and aircraft), the most important change has been the harmonization of railway fire protection standards in Europe, but there have also been many new developments in other parts of the world. Therefore, EU harmonization is covered in some detail, and sections on the USA and Canada, China, Japan, Korea, and Australia have been added.

The chapter on electrical engineering has been completely reworked and simplified in light of the progress made in the international harmonization of regulations and test methods. The growing importance of the fire performance of cables is now presented in a separate comprehensive section.

The chapter on furniture and furnishings concentrates on developments of fire safety regulations and testing in the USA and the UK, and has been revised in light of trends to deregulation caused by concerns regarding the use of flame retardants. A section on measurements and model prediction of the burning rate of furniture has been added.

Part III, "Appendices", contains various lists including a suppliers' index for flame retardants and smoke suppressants, a list of the most common abbreviations for plastics and flame retardants, the chemical names and CAS numbers of the latter, and a choice of journals and books devoted to flame retardancy and fire protection.

It is hoped that this book will be of interest to all those concerned with plastics, flame retardancy, fire testing, and fire protection, and will help the reader to better understand this complex subject.

Jürgen Troitzsch and Edith Antonatus
Ascona and Allensbach, January 2021

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training (origin of the fire, source of the fire, characteristics and circumstances of the fire, etc.), or for which they have insufficient time to give sound answers.

As a consequence, in Canada and the People's Republic of China, nearly all fire reports are filled in by fire officers who never received training in fire investigations. In other countries, such as Kenya, the Republic of Korea, Japan, and the USA, only a small number of fire reports are filled in by fire officers who received specially adapted training.

1.2.3 Current National Fire Statistics: Relevant Data on Specific Issues

Even if current fire statistics cannot be compared from one country to another (with a few exceptions), they can still be useful to describe the global fire safety situation and trends for a group of countries, or the specific fire safety situation of a country.

1.2.3.1 Number of Fires

In many countries, the trend is to a decreasing or (more recently) an unchanged number of fires. The number of reported fires and fires per million inhabitants for selected countries (USA [4, 5], Russia [6, 7], France [6, 8], UK [6, 9], Finland [6, 10], and Switzerland [6, 11, 12]) are illustrated in Figure 1.1 and Figure 1.2.

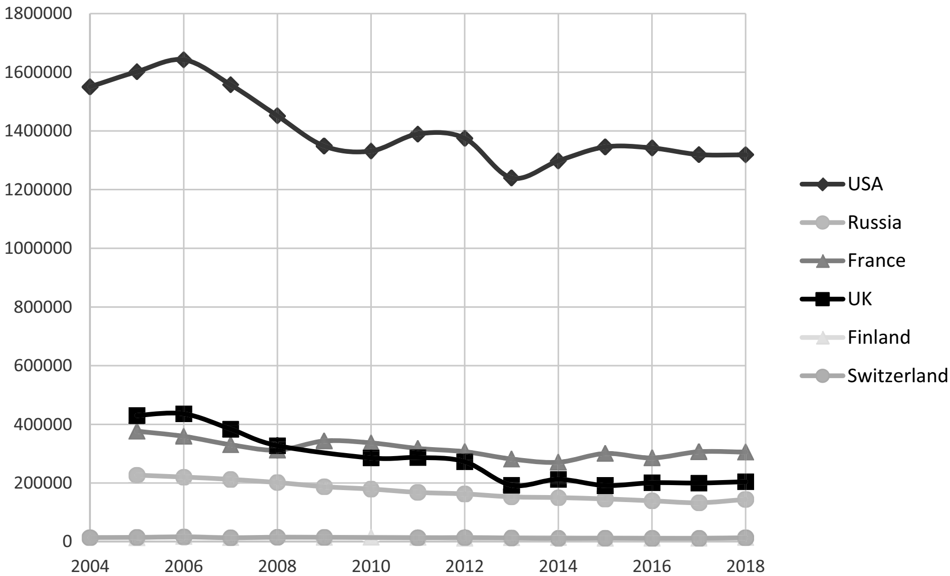

Figure 1.1 Number of fires in selected countries

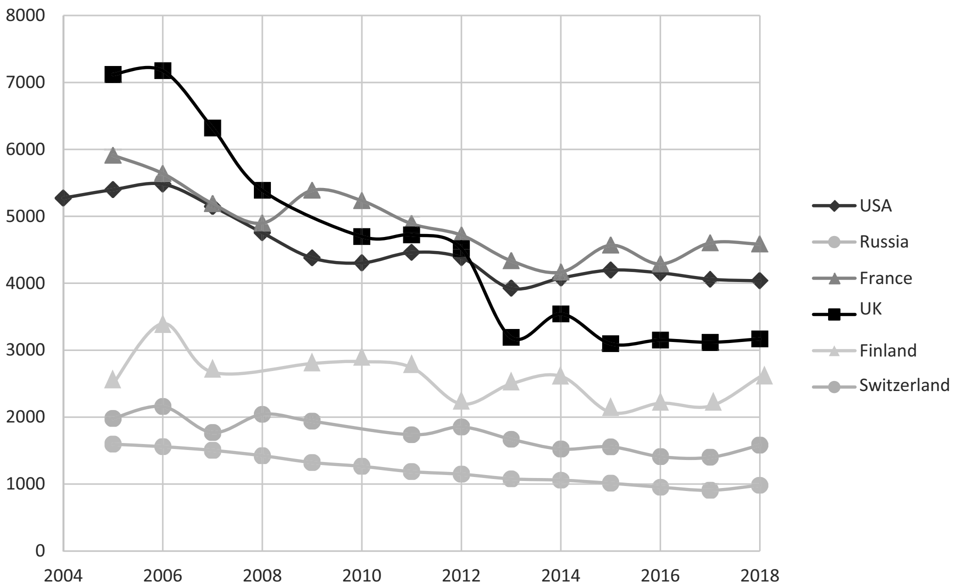

Figure 1.2 Fires per million inhabitants in selected countries

The analysis of the "World Fire Statistics" reports [6], published annually by the International Association of Fire and Rescue Service (CTIF), shows that for the 16 EU countries for which statistics were available (representing 62% of the EU population at that time), there was a decrease of 19% in the number of fires between 2006 and 2010.

Trend Uncertainties

The above statistics are called into question by recent local developments, which may reverse the global trend.

For example, in France, the last available Ministry of Interior official fire statistics [8] show an increase of 11% in the number of fires in 2015 compared to 2014. In the USA [4, 5], 1,240,000 fires were recorded in 2013, rising to 1,298,000 in 2014, representing an increase of 4.7% in one year.

In other cases, the situation seems to be unstable, with periods of increase followed by periods of decrease. An example is the number of fires in the Republic of Korea [13] from 2001 to 2009, shown in Figure 1.3.

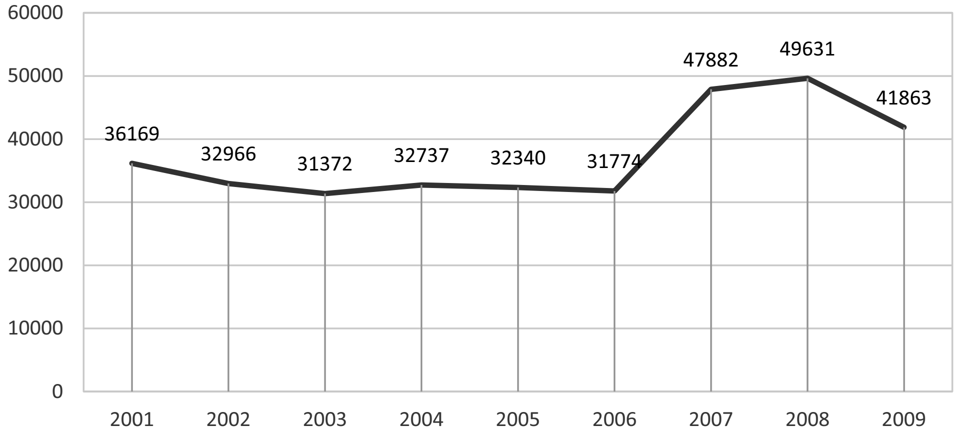

Figure 1.3 Number of fires in the Republic of Korea from 2001–2009

Local Trends to a Larger Number of Fires

As can be seen in Table 1.1, in some countries, the trend is to a larger number of fires; this may be due to an improved data collection system.

Table 1.1 Trend to a Larger Number of Fires in Selected Countries

Country	Number of reported fires					Change
	1995	2004	2006	2009	2010	
Poland [6]	72,391	–	–	159,122	–	+220%
Austria [6]	–	–	30,297	–	34,363	+13%
Ghana [6]	–	2,418	–	2,708	–	+12%

1.2.3.2 Number of Fire Fatalities

In many countries, a trend to a decreasing number of fire fatalities can be seen. However, in some countries, the situation is different and the number of fire fatalities is growing. In addition, some fire statistics show an unexpectedly high proportion of male fire fatalities, and also indicate that most fire deaths are recorded in residential building fires.

Decrease of Fire Fatalities in Many Countries

The number of fire fatalities and fire fatalities per million inhabitants for selected countries is illustrated in Figure 1.4 and Figure 1.5 (here, the curves for France are virtually covered by the UK ones).

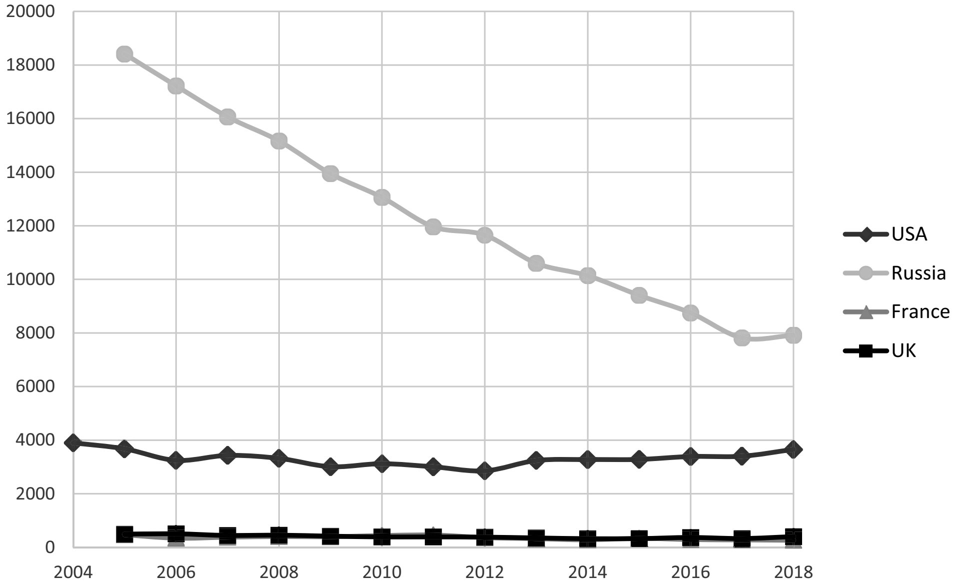

Figure 1.4 Number of fire fatalities in selected countries

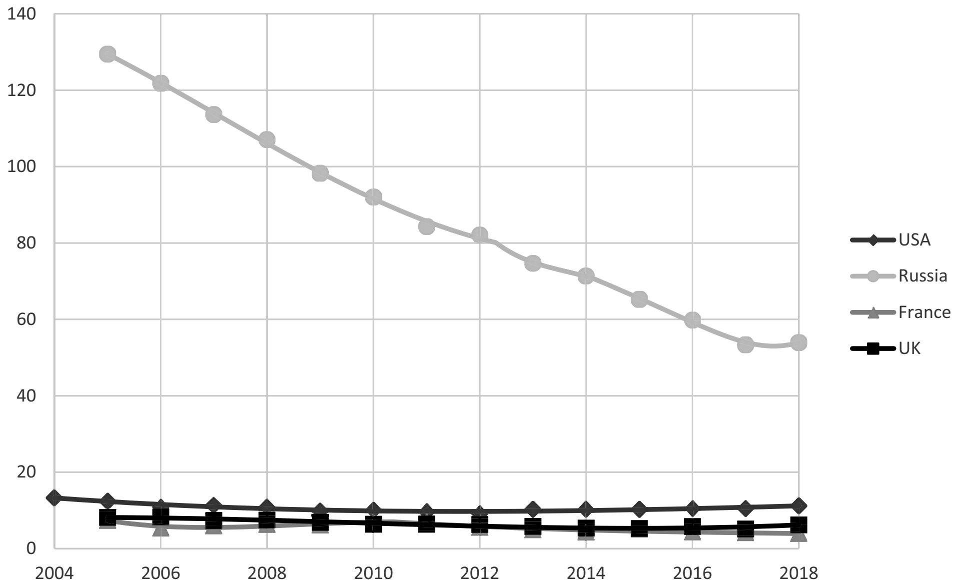

Figure 1.5 Number of fire fatalities per million inhabitants in selected countries

The “World Fire Statistics” issue no. 7 (published in 2012) covers the period 2006–2010, and shows that for the 19 EU countries for which statistical data were available (representing 74% of the EU population at that time), there was a decrease of 17% in the number of fire fatalities.

In the French official fire statistics, the number of fatalities at the location of fires (either discovered, or declared dead after unsuccessful resuscitation attempts) has decreased by 60% in the 32 years from 1982–2014, as summarized in Table 1.2.

Table 1.2 Total Number of Fire Fatalities Discovered at the Location of Fires

	Year						Difference	Change
	1982	1990	1999	2008	2012	2014		
Fatalities	702	579	460	402	362	280	422	–60%

Statistics on Japanese fire fatalities [15] show a significant proportion of suicides, and a higher-than-expected proportion of deaths of elderly people.

Trend Uncertainties

In the USA [4, 5], 2,855 fire deaths were recorded in 2012, increasing to 3,240 in 2013 and to 3,275 in 2014, representing an increase of nearly 15% in two years. In France, the Ministry of Interior’s official fire statistics [8] show an increase of 16% from the number of fire fatalities in 2014 (280) to 2015 (325).

All figures dealing with fire fatalities must be considered carefully. Indeed, the exact definition of a fire death is rarely specified in documents on fire statistics. Therefore, it is possible that a significant number of people with fire injuries died in hospital or during transport to it, and so may not have been counted in the final statement, skewing the final result.

In Ireland, the USA and Finland, the proportion of fire fatalities that were male was unexpectedly high, as shown in Table 1.3.

Table 1.3 Male Fire Fatalities in Selected Countries

Country	Year	Male fire fatalities	Female fire fatalities
Ireland [14]	2007	66%	34%
USA [4, 5]	2015	62%	38%
Finland [10]	2013	74%	26%

Fire Fatalities in Residential Buildings

Residential buildings contribute to most fire deaths because people live, cook, and sleep there.

In the official 2014 fire statistics published by the French Ministry of Interior in 2015, of the 280 fire deaths reported by the French Fire Departments, 228 fire fatalities were recorded in residential buildings, representing over 81% of all fire deaths. In a special study carried out by the Paris Police Laboratory for the three years 2012–2014, over 86% of all fire fatalities discovered at the location of fires by the Paris Fire Brigade (BSPP) were recorded in residential buildings, including one fire death in a residential high-rise building (IGH A). This is also true for some selected other countries, as shown in Table 1.4.

Table 1.4 Residential Fire Fatalities in Some Selected Countries

Country	Year	Proportion of residential fire fatalities vs total number of fire fatalities
Korea [13]	2010	65%
England [9]	2016/2017	82%
Finland [10]	2013	94%

1.2.3.3 Number of Fire Injuries

The term fire injuries is very difficult to define, and the differences between "minor injury", "moderate injury" and "severe injury" are numerous between countries – indeed, much more so than for "fire death". In some countries, there are even additional classifications – for example, in France, injuries are divided into "UR" (*Urgence Relative* = relative emergency) and "UA" (*Urgence Absolue* = absolute emergency).

Having highlighted these caveats, the current fire statistics show important differences in trends between countries. Figure 1.6 and Figure 1.7 summarize the number of fire injuries and fire injuries per million inhabitants for the USA [4, 5], Russia [6, 7], France [6, 8], and the UK [6, 9]. Here again, as for fire fatalities, we can note an unexpectedly high proportion of male fire injuries in some countries, and Table 1.5 shows the statistics for Spain [16] and the USA.

2.10(b) shows a computer simulation of such a non-flaming dripping V-0 behavior in a UL 94 test [63]. The simulated temperature demonstrates that in the UL 94 setup, the flame-retardant mode of action can be understood as an efficient cooling effect. The hot dripping removes enough energy so that the remaining slab extinguishes. In other tests, the effect is described as retreating from the ignition source. It is not only thermoplastics that show a large influence by melt flow and dripping at temperatures above their glass, melting, and decomposition temperatures, but also thermosets. For these, after a small delay, the pyrolysis products reach equilibrium above the decomposition temperature, yielding molten materials that behave quite similarly to thermoplastics.

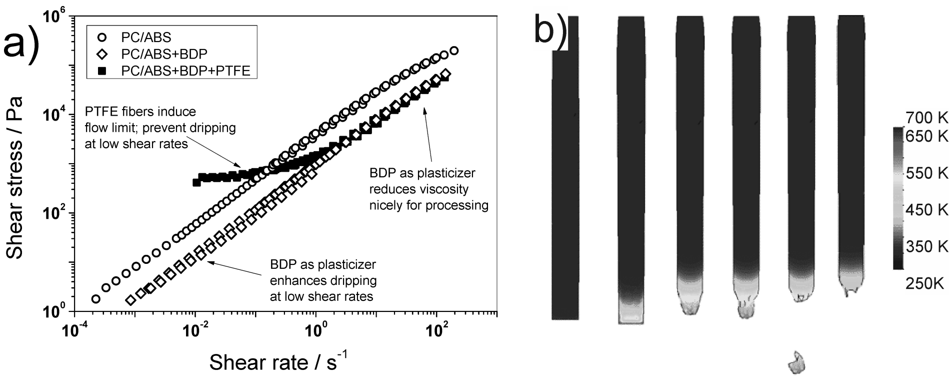

Figure 2.10 (a) Shear stress versus shear rate master curves (523 K) of PC/ABS (open circles), PC/ABS+BDP (open diamonds), and PC/ABS+BDP+PTFE (filled squares); (b) images of the PFEM simulation for extinction (V-0) of PP through non-flaming dripping

■ 2.4 Steady Burning and Flame Spread

Combustion is the exothermic process in which a fuel is rapidly oxidized, thereby consuming oxygen and producing heat and light. If the fuel is thoroughly mixed with air, and the amount of oxygen is constant, the ensuing combustion is complete; this is referred to as a “premixed flame”. In common fire scenarios, however, the amount of oxygen that can reach the fuel is limited by the laws of diffusion, hence the term “diffusion flame” [64]. A diffusion flame is characterized by its incandescent soot of a yellow-orange color, a result of incomplete combustion, as well as the lack of a clear flame front. Due to the dominating diffusion laws, the oxygen concentration from the periphery of the flame to its center is described by a gradient: the interfacial region at the material surface decomposes under anaerobic, pyrolytic conditions, while the flame zone above is characterized by thermo-oxidative reactions. In all cases, the high amount of thermal energy causes the bulk material to decompose and volatize, causing a flux of mass $\dot{m}''$ into the gas phase. The material flux is related to the combustion in the flame zone by the resulting effective heat flux $\dot{q}''_{eff}$ used for pyrolysis [3]:

$$\dot{m}'' \cdot L_g = \dot{q}''_{eff} \tag{2.8}$$

The conditions needed to produce a flux of fuel into the flame are dependent on the underlying decomposition reactions, which are inherently specific to the material's composition and its properties (heat capacity, heat conductivity, ratio of mass to surface area, etc.). The pyrolysis of the polymer results in the release of volatile fuel into the gas phase; covalent bonds of these fuel molecules are immediately broken further (bond scission) in the flame zone. This homolytic cleavage leads to the formation of two free-radical moieties, which is the first step in a vast series of chain reactions and is referred to as the initiation reaction (Figure 2.11). The reaction of a hydrogen radical with molecular oxygen is further known as the branching reaction, as both the resulting hydroxyl and oxygen radicals make a crucial contribution to the resulting radical chain reactions. The hydroxyl radical may interact with various combustion products, such as carbon monoxide, hydrogen, or hydrocarbons to form new free radicals, thus propagating the decomposition mechanism (Figure 2.11). Termination of the free-radical chain reaction occurs when two free radicals react with one another, as is the case when a hydroxyl and a hydrogen radical, or two hydrogen free radicals, interact to form water or molecular hydrogen, respectively (Figure 2.11).

Initiation:	$RH \rightarrow R\bullet + H\bullet$
	$C_nH_{2n+2} \rightarrow C_{n-1}H_{2n-1}\bullet + CH_3\bullet$
Branching:	$O + H_2 \rightarrow OH + H$
	$H\bullet + O_2 \rightarrow HO\bullet + O\bullet$
Propagation:	$HO\bullet + CO \rightarrow CO_2 + H\bullet$
	$HO\bullet + H_2 \rightarrow H_2O + H\bullet$
	(C_xH_n consumption)
	$RH + HO\bullet \rightarrow RH\bullet + H_2O$
	$RH + O \rightarrow RH\bullet + HO\bullet$
	$RH_2 + H\bullet \rightarrow RH\bullet + H_2$
	$RH\bullet + O_2 \rightarrow RO + HO\bullet$
	…
	$HCO\bullet \rightarrow CO + H\bullet$
Most exothermic:	$CO + HO\bullet\cdot \rightarrow CO_2 + H\bullet\cdot$
Termination:	$H\bullet + HO\bullet \rightarrow H_2O$
	$H\bullet + H\bullet \rightarrow H_2$

Figure 2.11
Scheme of oxidative chain reaction in the flame

Of the abundant and complex free-radical reactions taking place in a fire scenario, the formation of carbon dioxide (and a hydrogen radical) from the reaction of hydroxy free radicals with carbon monoxide is the most exothermic reaction and is the largest contributor to the heat released in a fire scenario.

The sum of all exothermic reactions in a fire scenario is known as the total heat released (THR); it is the integral of the heat release rate (HRR) curve over time. The HRR is most commonly determined by measuring oxygen consumption, and the equation used to calculate the HRR considers the material's behavior under fire conditions and the heat fluxes working upon it. When ignition is continuous and the burning rate is constant, the HRR of the material is equal to the product of the combustion efficiency χ, the heat of complete combustion of fuel gases h_c and the mass flux $\dot{m}''$, which, according to Eq. (2.9), is related to the net heat flux $\dot{q}''_{net}$ via the enthalpy of gasification L_g [1]:

$$\mathrm{HRR} = \chi \cdot h_c \cdot \dot{m}'' = \chi \frac{h_c}{L_g} \dot{q}''_{net}$$

$$\dot{q}''_{net} = \dot{q}''_{ext} + \dot{q}''_{flame} - \dot{q}''_{rerad} - \dot{q}''_{loss} \tag{2.9}$$

The combustion efficiency χ is the ratio between the measured effective heat of combustion (HOC) and the heat of complete combustion h_c; its values range from χ =1 for complete and χ < 1 for incomplete oxidization. It depends somewhat on the material burning, but also on the ventilation of the fire scenario. Flame inhibition, one of the most important modes of action used in flame-retarded polymers, reduces the combustion efficiency considerably. The net heat flux used for pyrolysis can be written as the sum of the heat fluxes in steady flaming combustion (Eq. (2.5), Eq. (2.9), Figure 2.1, Figure 2.8), where $\dot{q}''_{ext}$ is the external heat flux working upon the material per unit area, $\dot{q}''_{flame}$ is the heat flux of the flame, $\dot{q}''_{rerad}$ is the heat flux caused by reradiation of the hot surface to the environment, and $\dot{q}''_{loss}$ is the loss of heat into the specimen and surrounding environment, such as the specimen holder. The product of combustion efficiency and the ratio of heat of complete combustion of the fuel gases to enthalpy of gasification is known as the heat release parameter HRP [1]:

$$\mathrm{HRP} = \chi \cdot \frac{h_c}{L_g} = \chi \cdot (1-\mu) \cdot \frac{h_c}{h_g} \tag{2.10}$$

A time dependent factor ($\theta(t)$) between 0 and 1 may be introduced for the influence of the protective residual layer formed during burning. When these factors are combined, the resulting equation describes the dependency of the HRR on the heat release parameter, the protective layer, and the net heat flux (Eq. (2.11)).

$$\mathrm{HRR}(t) = \chi \cdot \theta(t) \cdot (1-\mu) \cdot \frac{h_c}{h_g} \cdot \left(\dot{q}''_{ext} + \dot{q}''_{flame} - \dot{q}''_{rerad} - \dot{q}''_{loss}\right) \tag{2.11}$$

HRR is believed to be the most important fire property to assess the fire hazard of materials [65]. Therefore, Eq. (2.11) is highlighted as the most important statement of this chapter. Apart from the parameter of heat absorption, which is set to 1 and thus neglected, it combines all of the important characteristics controlling fire behavior, including char yield, combustion efficiency, heat of combustion of the volatiles, and heat of gasification. The empirical factor $\theta(t)$ is added arbitrarily to account for the changing protective layer properties of the fire residue during burning, which results in HRR changing as a function of t. This may be superfluous if h_g is used as $h_g(t)$ to account for the impact of the residual protective layer, for instance, or if Eq. (2.11) is used to describe a constant, steady state HRR. Thus, in all relevant sources [1–3], Eq. (2.11) is always given without $\theta(t)$; thus, $\theta(t)$ may be ignored or added as an empirical contribution after the fact.

However, it must not escape our notice that without $\theta(t)$, Eq. (2.11) also covers the greatest effect of residual protective layers: the heat shielding effect. In contrast to the effects of absorption in depth and heat reflection mentioned at the beginning of this chapter, heat shielding is not connected to reduced heat absorption or increased heat reflection but is based on increased reradiation of the hot surface $\dot{q}''_{rerad}$. The heat shielding effect has been reported as the most important flame-retardant mode of action in layered silicate nanocomposites of non-charring polymers, for instance; in some systems, it may be the only relevant one [38]. The key to understanding this is to apply Eq. (2.1) and quantify the role (to the fourth power) of the surface temperature T in $\dot{q}''_{rerad}$ of Eq. (2.11). The surface temperature of non-charring polymers equals their pyrolysis temperature, whereas the carbonaceous, inorganic-carbonaceous, or inorganic residual layer can heat up to much higher temperatures. Thus, jumping from a pyrolysis temperature of 420 °C to a residue surface temperature of 720 °C entails an increase in $\dot{q}''_{rerad}$ from 10 kW/m^2 to 50 kW/m^2, compensating for the feedback from a flame or the external heat flux in a cone calorimeter experiment.

Once a material is successfully ignited, the flame is stable and starts expanding, known as flame spread. This can happen in air, along surfaces, or through porous solids [66]. It means that the affected area always offers enough combustible material to supply the flame. With respect to the quality of the fuel, an adequate amount of fuel must be provided over time. The phenomenon can be regarded as many small fuel elements igniting one after the other. The velocity of the flame spread depends on how fast the nearby fuel elements are heated up to the ignition temperature (T_{ig}). The heat flux can be provided by the burning material or other external sources. If the current element is not burning intensively or long enough to ignite the next one, the flame extinguishes [67]. Flame spread is the most important fire hazard in developing fire, but must not be confused with fire spread. Fire spread means the advancing of a fire front and thus can be flaming or smoldering [66].

The speed of the flame spread depends on its mode. For wind-aided flame spread, the air flows in the same direction as that in which the front of the flame is propagating. Another expression for this is concurrent flow. For opposed flow flame spread, the air flows in the opposite direction from the flames. Natural flow is caused by the buoyancy of the flame. Thus, if the specimen's surface is horizontally aligned, there is an opposed flow in all directions of the plane. If the specimen is aligned vertically, there is a strong wind-aided flame spread upwards and a much smaller opposed flow flame spread downwards (Figure 2.12). In contrast to natural flow, forced flow is produced by meteorological flow or a fan. The principle remains the same for wind-aided or opposed flame spread. The flow conditions affect the distance affected directly by the flame δf and thus the velocity of the flame spread [66]. By the way, this very different area of material in direct contact with the flame is also the main difference between vertical UL 94 and OI, which assess wind-aided and opposed flow flame speed, respectively. Furthermore, the flame temperature of many solids decreases with a lower oxygen concentration in the air. This often limits the flame spread on room ceilings [68], which is a good example of a natural wind-aided flame spread [66].

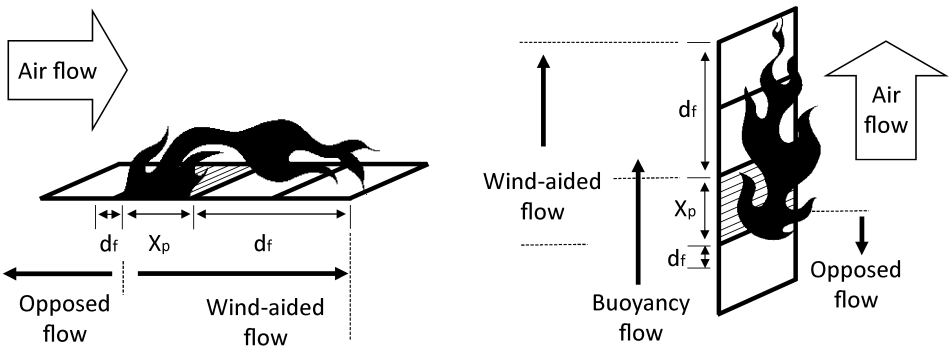

Figure 2.12 Illustration depicting wind-aided flame spread and opposed flow flame spread

The velocity v of flame spread is given by the difference between the energy provided by the heat flux from the flame to the fuel length δf and the energy required to heat up to the ignition temperature. The heat flux depends on the heat release rate of the material. For a thermally thin material with a thickness d, using Eq. (2.7), this balance can be expressed as [66, 68]:

$$v \cdot \rho \cdot d \cdot c_p \cdot \left(T_{ig} - T_0\right) = \dot{q}''_{flame} \cdot \delta_f$$

$$v = \frac{\dot{q}''_{flame} \cdot \delta_f}{\rho \cdot d \cdot c_p \cdot \left(T_{ig} - T_0\right)} = \frac{\delta_f}{t_{ig}} \qquad (2.12)$$

For a thermally thick specimen:

$$v = \frac{\delta_f}{t_{ig}} = \frac{(\dot{2q}''_{flame})^2 \cdot \delta_f}{\pi \cdot \rho \cdot k \cdot c_p \cdot \left(T_{ig} - T_0\right)^2} \tag{2.13}$$

■ 2.5 Fire Load and Fire Resistance

In a fully developed fire, all combustible materials are believed to be on fire, and therefore this state is characterized by extreme high heat fluxes and temperatures. The fire safety objectives have changed. Ignitability, flammability, reaction to fire, and burning behavior are no longer substantial; the point is to gain time for evacuation and firefighting before the collapse of the construction and to prevent the fire from spreading further. The crucial fire properties in a fully developed fire scenario are fire load and fire resistance. Fire load is the quantity of heat that can be released during the complete combustion of all the combustible materials involved (ISO 13943). To assess the fire load of certain materials, measurements in the bomb calorimeter, cone calorimeter, or micro combustion calorimeter (MCC or pyrolysis combustion flow calorimeter, PCFC) are used [1]. In the bomb calorimeter, the specimen is combusted completely under a pure oxygen atmosphere. The result is the net heat of combustion per mass of the specimen, which can be used to calculate the worst-case fire load. More realistically, the total heat evolved (THE) in the pyrolysis of polymeric materials, along with their distinct char yields, is determined by integrating the heat release rate measured in the cone calorimeter or the MCC. Thus, the cone calorimeter delivers the HOC for a real specimen in a well-ventilated fire, and the MCC the h_c for the complete combustion of the volatiles as discussed earlier. Along with the mass of the products or components, the fire load can be assessed. Apart from the calorimetric assessment, non-combustibility tests are performed, such as ISO 1182 on construction products of the highest classification in Europe. The cylindrical specimen is placed in a preheated electric furnace, and the mass loss and temperature rise caused by the specimen are monitored within the high-temperature furnace. Since these tests also focus on complete combustion, all polymeric materials, which are generally combustible, usually fail such tests.

Fire resistance is the ability of a test specimen to withstand fire or give protection from it for a period of time (ISO 13943). Fire resistance is usually a property of a component rather than a material. Fire resistance properties are relevant only for polymeric materials used in fire-resistant components, systems, and structures. Common criteria are fire stability, thermal insulation, or functioning as a barrier for heat, fire, and smoke for a certain time. Fire resistance is often tested in nearly

7.3 Toxicological Risk Assessment

7.3.1 Definition of Uncertainty

In combustion toxicology, an exposure dose is defined as any pre-specified amount of toxic substances exposed to over a specified duration eliciting a certain, well-defined response (binary) or effect (continuous). A response algorithm can be judged as a binary simplification of a continuous relationship. Inhalation toxicology defines the response to a given dose "$C \times t$" as the quantification of a biologically relevant effect and as such it is subject to random variation. The traditional interpretation of dose–response information is to accept the existence of a threshold level of dose that must be inhaled to produce the toxic effect. Thus, a threshold or POD exists if there is no effect below a certain exposure level, but above that level the effect is certain to occur. The POD is defined as the point on a toxicological dose–response/effect curve established from experimental data generally corresponding to an estimated low (adverse) effect level or no (adverse) effect level. As exemplified, not all effects we see are necessarily adverse. This applies especially to sensory irritants and their psychophysical sequelae. This threshold marks the beginning of extrapolation to toxicological reference concentration values that can be calculated by dividing the POD with corresponding uncertainty or adjustment factors as illustrated earlier. These factors are used to address the differences between the experimental data and the specific human situation of interest, considering the following major uncertainties in the extrapolation procedure: inter- and intraspecies differences, differences in duration of exposure of data from bioassays and targeted human exposure, issues related to dose–response, and quality of whole database.

There is a consensus amongst toxicologists and risk assessors that uncertainty factors have to be accommodated when applying PODs from animal studies to a specific population at risk. However, in the case of fire accidents, the scope is to minimize failure of an escape event experienced once in a lifetime. There is likely to be considerable variability in the escape responses of different individuals affected by such an incident. Similarly, the concentrations of toxic fire gases released over time may change dramatically with great variability from one location to another. Many of the available toxicity data are not usually adequate for predicting precise dose–time–response/effect relationships. Smoke obscuration and heat may readily become a greater threat than that originating from toxicants. Thus, the prediction of effective cumulative exposure doses for a given scenario is more complex than the concept of a fractional effective dose (FED) used as a tool to assess the toxicity-related impact on the impairment of escape as defined by the International Standard ISO 13571 [7]. This standard defines an FED (for asphyxiants) and an FEC (for irritants) value of 1.0 as the median value of a lognormal distribution of the ability to perform an escape response within a defined time window. Any failure to perform this task would inevitably result in fire-related fatalities. Post-exposure deaths or irreversible outcomes may not entirely be prevented by this standard. An FED or FEC of 0.1 translates to a ≈ 1% population response. More recently suggested modifications of this standard are detailed elsewhere [2, 3].

The wealth of physiological and toxicological information available on rats reduces the uncertainty when extrapolating findings from this species to humans. Harmonized guidance has been published for applying inter- and intraspecies uncertainty factors to adjust inhaled doses and for applying findings from this species to humans. To the contrary, data from non-human primates cannot rely upon a strong database and the species-specific inhalation methodology is less standardized and is subject to laboratory-specific outcomes. Therefore, such unique studies can only be judged as supplemental rather than core evidence. For most of the asphyxiant toxicants, similar modes of action in animals and humans can be assumed with no interspecies factor required. Dosimetrically, the rats' respiratory ventilation is high and conservative enough to omit the variability in human activity-related differences in ventilation. However, as exemplified for ammonia, for respiratory tract irritants, it appears to be indispensable to consider in detail concentration-, modes of action-, and species-specific response-based dosimetric adjustments.

7.3.2 Analysis of Time–Dose–Response Relationships

7.3.2.1 Asphyxiants

Published analyses on the time-scaling of data from acute inhalation studies on rats used the ten Berge algorithm "$C^n \times t = k$ (constant effect)" [2, 47, 58]. By introducing the toxic load exponent (n), multiple inhalation studies with variable exposure concentrations (C) and exposure times (t) can be combined to calculate the LC_{50} and LC_{01} from the entire matrix of data. The exponential weighing factor was incorporated to better describe the relative contribution of C and t mathematically; however, for practicability, either the toxic load "n" or the toxic load "k" is a combination of both. For HCN and CO, the calculated "n" was 1.64 and 1.77, respectively. The related toxic load constants for the non-lethal threshold "$k(LCt_{01})$" were 0.109×10^6 and 0.498×10^8 [$ppm^n \times min$], respectively. The median lethal concentrations "$k(LCt_{50})$" were 0.294×10^6 and 1.21×10^8 [$ppm^n \times min$], respectively (Figure 7.7). This parameterization was derived from published nose-only inhalation studies in rats and is valid for exposure durations up to 60 min [2, 47–49].

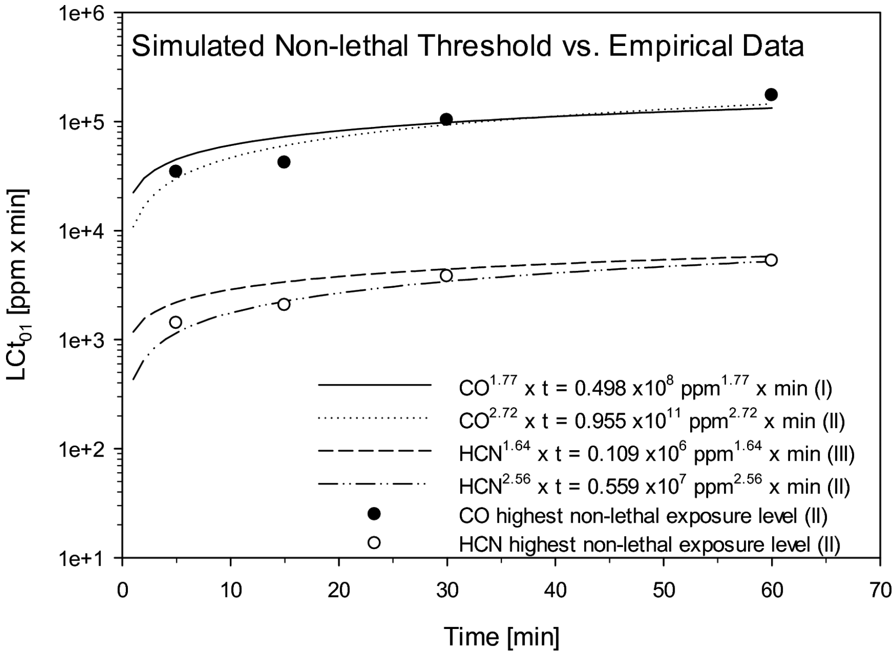

Figure 7.7 Toxic load model with C^n x t = const. effect. The non-lethal threshold (LCt_{01}) values of CO and HCN were calculated based on the multiple $C \times t$ relationships of nose-only exposed rats as detailed elsewhere [2] (figure reproduced from Pauluhn, 2016 [2])

Despite the different modes of exposure (nose-only vs. whole-body) and the applied technical standards, the calculated LC_{01} of both studies were similar at 30 and 60 min exposure durations (Figure 7.7). Differences between modes of exposure may occur due to the restraint-related higher ventilation in nose-only exposed animals. Recent OECD testing guidelines consider nose-only studies superior to whole body studies as technical mishaps are less likely to occur [4, 5]. The comparison given in Figure 7.7 illustrates that the "toxic load model" provides a versatile means to calculate the cornerstones of acute inhalation toxicity LC_{50} and LC_{01} from the entire $C \times t$ matrix examined. Therefore, the comprehensive data sets from rats were given preference to isolated data using non-standardized approaches. Concurrent with the rationale given earlier, the $1/3 \times LC_{01}$ relationship was taken as a threshold below which no impairment of escape is expected to occur [2]. As illustrated in Figure 7.8, the $C^n \times t = k$ relationship is suitable to calculate any time-adjusted LCt_{01} from any set of mortality data with multiple exposure durations. It appears to be reasonable to expand this equation to also calculate the incapacitation threshold (IC_{01}) with $IC_{01} = LC_{01} \times 1/3$ as shown below.

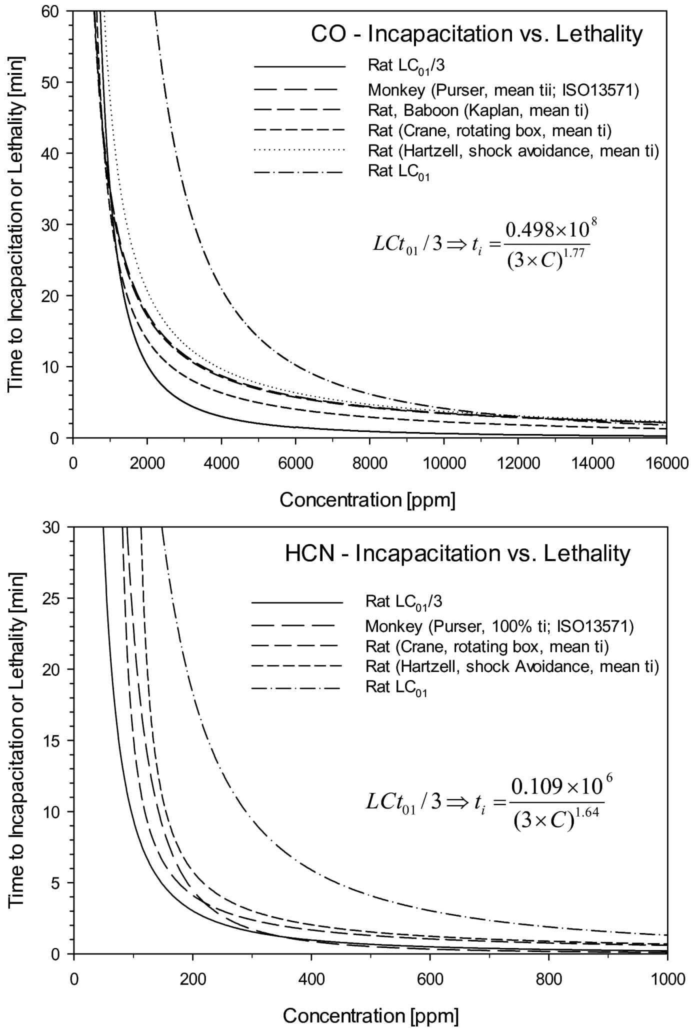

Figure 7.8 Comparison of the time-to-incapacitation in rats and non-human primates using four different endpoints to characterize incapacitation. Data were from Sweeney [48–50], Purser [51, 52], Crane [18], Kaplan [53], and Hartzell [19] as summarized by Speitel (1995) [32] (figures reproduced from Pauluhn [2])

Thus, despite their underlying different endpoints, the empirical $C\times t$ relationships support the $1/3 \times LC_{01}$ approach as sufficiently conservative. As long as this threshold is not exceeded, "impairment of escape" and post-exposure lethality will not occur. Thus, the statistically derived descriptor of toxicity POD_1 (lethality) can suitably serve as a starting point for calculating the POD_2 (incapacitation). Lethal and non-lethal POD from standardized, testing guideline-compliant acute inhalation studies on rats commonly serve as the most important cornerstones for deriving such guidance levels for chemical emergencies [8].

Mortality-based data commonly serve a broader range of exposure concentrations and durations than studies aiming solely at t_{inc}, the time to attain incapacitation. They also follow more rigid and internationally harmonized testing protocols using sufficient number of rats instead of few non-human primates with limited baseline data and benchmark validations [4, 5]. This facilitates enormously their use for hazard analysis and comparisons across different laboratories. The resultant broader and more consistent database outweighs the conceived advantage of duplicating a more "human-like" incapacitation paradigm. The surrogate endpoints used in animal bioassays for defining t_{inc} often require conditioned animals for the applied performance tests and used titration towards incapacitation. High inter-animal variability occurs at subtoxic exposure levels and either dichotomous or continuous endpoints are used. Accordingly, extrapolation errors appear to be less likely to occur when starting with a unequivocal binary endpoint to be determined simultaneously in equally exposed animals in the absence of superimposed methods of detection. These aspects give preference to the $IC_{01} = 1/3 \times LC_{01}$ approach as compared to laboratory-specific, fine-tuned, and highly specialized neurobehavioral testing batteries [2]. Titration of t_{inc} in single larger animals can hardly serve the purpose of probabilistic assessments due to animal- and method-specific variabilities.

7.3.2.2 Irritants

As referred to above, airborne chemical sensory irritants are known to evoke a burning sensation in the eyes, nose, and throat, thereby causing "impairment of escape" in an exposed individual. At high concentrations, exposure can be both incapacitating and life-threatening. Animal models were developed using the decrease in respiratory rate in mice or rats as an index of sensory irritation. Based on the concentration–response relationships, the RD_{50}, defined as the concentration causing a 50% decrease in respiratory rate, was shown to have a predictable relationship with sensory irritation in men [54–57]. The interrelationship of the RD_{50} and other descriptors of acute toxicity is compared for hydrogen hydrochloride (HCl) in Figure 7.9. Although sensory irritation occurs concentration-dependently, its severity is better described as a $C^n \times t$ dependent response [8–10]. As exemplified for HCl, the lethality-based $LC_{01}/30$ and SLOT-dangerous toxic load (DTL)/10 values correspond favorably to the AEGL-2 to AEGL-3 range (see Figure 7.9). Taken as a whole, these findings suggest that defined fractions of the LC_{01} and SLOT values are suited to serve as a basis for the estimation of threshold $C^n \times t$ values below which incapacitation can be excluded with reasonable probability.

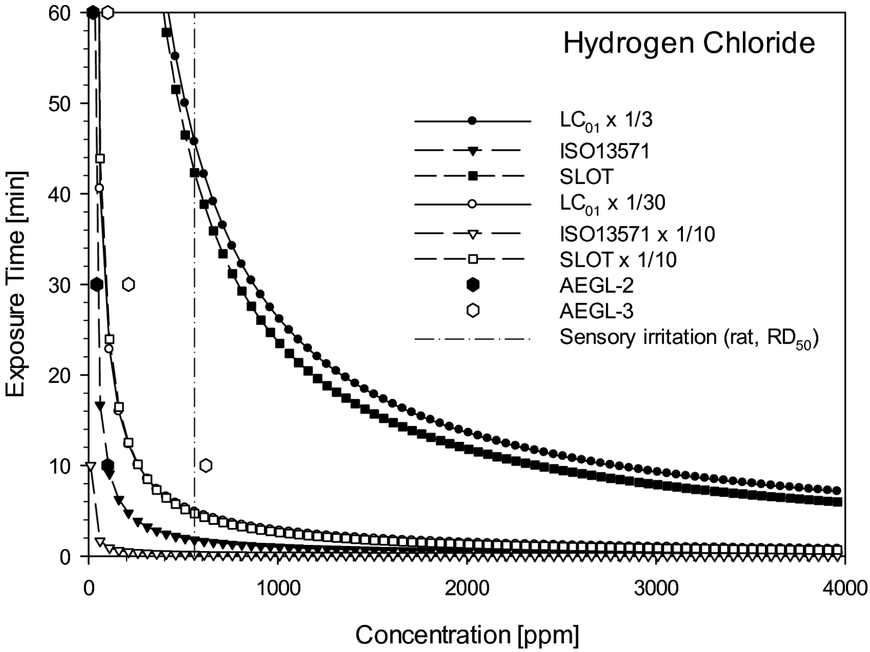

Figure 7.9 Concentration x exposure time comparisons of the irritant gas HCl. The toxic load $C^n \times t$ = const. effect model used the published parameterization of SLOT-DTLs [10] for the general population. The 1/30 × LC_{01} from rats exposed to HCl was taken as a reference to demonstrate the implicit conservatism of the course taken

It is interesting to note that the SLOT (DTL) principle [10] arrives at the same conclusion for both asphyxiant and irritant chemicals by using the toxic load model but different rationales for the same uncertainty factor to account for variability of the human population (Figure 7.9) [10]. When looking at the SLOT criteria, they reflect exposure conditions just on the verge of causing a low percentage of deaths in the exposed general population. It takes around 1% mortality in animals (LC_{01}) as being representative of SLOT conditions. They are used to provide estimates of the extent (i.e., hazard ranges and widths) and severity (i.e., how many people are affected, including the numbers of fatalities) of the consequences of each identified major accident hazard [10, 11]. The comparison of the SLOT-DTL/10 with the LC_0/30 relationships given in Figure 7.9 supports the notion that SLOT-DTL/10 appears to be a defensible estimate for assessing the irritation-related threshold for incapacitation.

- Better control of building materials and products
- Continued maintenance of buildings and relevant parts and components.

Regarding full-scale tests for façades, the European Commission is currently trying to develop a harmonized full-scale test method, but an international discussion has started as well. In a number of countries, regulations for high-rise buildings are under review or have been reviewed, and the international scientific community is focusing on the topic of fire safety of façades.

Another discussion relates to toxicity of combustion gases from construction products. While in Europe, Australia, and the USA (except New York) this topic is currently not considered as relevant for fire safety, some Asian countries have introduced toxicity requirements for construction products. Most countries rely on the approach that it is key to prevent people from exposure to smoke, because smoke is always toxic. The European Commission has commissioned a study confirming this approach [2]. But the discussion is ongoing, and further requirements for combustible building products may come up in the future.

References for Section 10.1

[1] Regulation (EU) No. 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.

[2] Study to evaluate the need to regulate within the Framework of Regulation (EU) 305/2011 on the toxicity of smoke produced by construction products in fires, European Commission, 2017.

10.2 Americas

Marc Janssens

10.2.1 United States of America

10.2.1.1 Statutory Regulations

An acceptable level of fire safety is accomplished for new or substantially renovated construction through compliance with local regulations. These regulations are based on national model building codes. Additional regulations based on a national model fire prevention code ensure that this level of fire safety is maintained during the lifespan of the building. The U.S. model codes are largely prescriptive. Acceptance criteria for construction materials, products, and assembly designs are generally based on performance in standardized fire tests. The following sub-sections provide a brief overview of the model code system in the USA.

For a more comprehensive review, the reader is referred to the book by Diamantes [1].

U.S. Model Codes

There are two model building and fire prevention code organizations in the United States; the International Code Council (ICC) [2] and the National Fire Protection Association (NFPA) [3].

ICC was formed in 1994 as an umbrella organization consisting of representatives of three older model code organizations: Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO) and Southern Building Code Congress International (SBCCI). The purpose of ICC was to facilitate the development of a single set of model codes to replace the codes maintained by BOCA, ICBO and SBCCI, i. e., the National, Uniform, and Standard codes respectively. The BOCA, ICBO and SBCCI codes served for many years as the basis for local fire safety regulations in Northeastern, Southern, and Western regions of the country. Although the ICC member groups agreed to discontinue their individual codes in 2000, many local jurisdictions did not immediately transition and continued to rely on the older documents for several years. At the time of this writing, the older regional codes have been superseded by national ICC and NFPA codes throughout the U. S.

ICC promulgates the International Building Code (IBC) and the International Fire Code (IFC). The IBC and IFC are supplemented with a series of model code documents that provide more detail and additional requirements for specific types of buildings (e. g., one- and two-family dwellings) and specific building systems and components (e. g., plumbing), or to achieve specific objectives (e. g., mitigate risks to life and property from wildfires). Collectively, the IBC, IFC, and supplemental documents are referred to as the International Codes®, or I-Codes®. New editions of the I-Codes are published every three years. The I-Codes can be viewed online for free [4]. The free access is referred to as publicACCESS™. A subscription to premiumACCESS™ is required for users who want to print sections of a code, search and annotate the document, or need other advanced features. In the District of Columbia and the states of Arizona, Kansas, and Nevada the I-Codes are adopted by jurisdictions at the local level. In the remaining states, the I-Codes are adopted statewide, although local jurisdictions in some states are allowed to amend the state code and include more stringent requirements.

In 2003, NFPA published the first version of its model building code, NFPA 5000. A new edition is published in the same year as the IBC. In addition, NFPA promulgates a fire prevention code and the *NFPA 101: Life Safety Code®*. The latter is widely used throughout the country but is primarily concerned with occupant safety in specific types of buildings and does not address all building construction and fire prevention issues. NFPA also maintains codes that are included in the I-Codes by reference. The most noteworthy of these is the *NFPA 70: National Electrical Code®*. At this time NFPA 5000 has not yet been adopted by a local jurisdiction. NFPA codes and standards can also be viewed online for free [5].

Demonstrating Compliance with Building Code Fire Safety Requirements

Fire protection of buildings addresses all aspects of fire safety and consists of a combination of active and passive measures. Active fire protection devices such as sprinkler, smoke control, and detection and alarm systems require manual, mechanical, or electrical power for their operation. Testing of active fire protection devices is beyond the scope of this handbook. Passive fire protection does not require any external power. There are essentially two types of passive fire protection measures that involve fire testing of construction products, structural elements, and assemblies.

The objective of the first type of measures is to reduce the likelihood of ignition and limit the rate of fire growth to the critical stage of flashover in the compartment of fire origin. A slow-growing fire leaves more time for safe egress of building occupants, and generally results in reduced property damage at the time of manual or automatic suppression. This can be accomplished by using interior finishes and furnishings with specific ignition, flame spread, and heat release characteristics. These characteristics are determined based on performance in standardized tests that expose a specimen to the thermal environment representative of the initial stages of a fire. Standardized tests are also used to control ignition of and flame spread over exterior façade and roof surfaces. A secondary objective of the first type of measures is to control the quantities of particulate matter (which affects visibility) and of toxic products of combustion that can cause human casualties and excessive damage to equipment. The city of New York is the only jurisdiction in the U.S. that specifies a smoke toxicity requirement for construction products in its building code[1].

Despite the first type of measures, fires do grow to full involvement of the room of origin. When this happens, the focus shifts to containing the fire within a limited area, at least for a certain time. Thus, fire spread to other parts of the building or adjacent buildings is delayed or prevented. This containment process is referred to as compartmentation. It is accomplished by providing fire-resistive floor, wall, and ceiling assemblies and by protecting openings and penetrations through room boundaries. Compartmentation also involves protecting structural elements and assemblies to avoid or delay partial or total collapse in the event of fire.

[1] § 803.5 of the New York City Building Code® [6] requires that interior wall or ceiling finishes, other than textiles, upon exposure to fire, shall not produce products of decomposition or combustion that are more toxic than those given off by wood or paper when decomposing or burning under comparable conditions as tested in accordance with NFPA 269: *Standard test method for developing toxic potency data for use in fire hazard modeling.*

To demonstrate compliance with fire safety requirements in the code, the architect or builder typically needs to present a report from an accredited laboratory to the code official that confirms that the product, structural element, or assembly was tested according to the applicable standard method and meets the acceptance criteria specified in the code. Most accredited fire testing laboratories publish a directory of tested products. These directories facilitate the code official's job to verify compliance and determine which variations from the tested product, element, or assembly are acceptable (e. g., acceptable range of thicknesses, substrates, and adhesives, etc.)

Generally, there is no requirement that tested products be listed, labeled, and subject to periodic follow-up plant inspections and verification testing, although there are exceptions. For example, the IBC requires that fiber-reinforced polymers delivered to the job site shall bear the label of an approved agency showing the manufacturer's name, product listing, product identification and information sufficient to determine that the end use will comply with the code requirements.

Product manufacturers sometimes develop a new product or identify a new application for an existing product that does not meet the established building code requirements. In 2003, the ICC created a technical evaluation service (ICC-ES) [7], which determines whether such a product or application meets the intent of the building code. If that is found to be the case, ICC-ES identifies a test method or develops a calculation method to evaluate the product, and establishes acceptance criteria. The results of the technical evaluation are published in a report. Presentation of the evaluation report to the code official serves as an alternative approach to demonstrate building code compliance. Testing in support of an evaluation report shall be performed by an accredited laboratory. New acceptance criteria developed as part of a technical evaluation are published in a separate document, which facilitates future evaluations of the same type of product or application requested by other manufacturers (or later by the same manufacturer). In recent years several accredited fire testing laboratories, third-party quality assurance agencies, and fire consulting engineering firms have developed competing evaluation services.

Testing Laboratory and Third-Party Quality Assurance Agency Accreditation

Testing in support of building code compliance can only be performed by accredited laboratories. There are two independent organizations in the U. S. that provide this type of accreditation service for fire testing laboratories: the American Association for Laboratory Accreditation (A2LA) [8] and the International Accreditation Service (IAS) [9]. Both use the requirements and criteria described in ISO/IEC 17025 [10]. As a result, a laboratory has to demonstrate an internationally recognized level of competence to be accredited. A2LA and IAS accreditations only cover specific standard test procedures. The test methods for which a laboratory is accredited are listed on the certificate, which can be printed from the A2LA and IAS websites. Both A2LA and IAS also accredit agencies that offer a listing, labeling, and follow-up inspection program for products that (in accordance with the code) require third-party quality assurance (QA). In this case, the agencies are periodically assessed according to the guidelines and criteria in ISO/IEC 17020 [11]. Table 10.1 provides a list of the fire testing laboratories in the U.S. that are accredited by IAS. The table also indicates for each laboratory whether it has an accredited third-party QA program and can perform some of the most common standardized fire test methods referenced in the IBC. A complete list of tests can be found on the IAS certificate. Only the laboratories that offer QA services have a directory of tested products.

Table 10.1 IAS-Accredited Fire Testing Laboratories Located in the U.S.

Fire testing laboratory	QA	ASTM standards				NFPA standards	
		E84	E108	E119	E136	285	286
Architectural Testing [12]	✓	✓	✓	✓	✓	✓	✓
FM Approvals [13]	✓	✓	✓	✓			
Intertek Testing Services [14]	✓	✓	✓	✓	✓	✓	✓
NGC Testing Services [15]		✓	✓		✓		
QAI Laboratories [16]	✓	✓	✓		✓		
Southwest Research Institute [17]	✓	✓	✓	✓	✓	✓	✓
Underwriters' Laboratories [18]	✓	✓	✓	✓	✓	✓	✓
Western Fire Center [19]			✓	✓			

10.2.1.2 Consensus Standards

In general, the building code fire safety requirements for products, structural elements, and assemblies are based on performance in a standardized test developed according to a consensus process. The primary consensus-based organizations in the U.S. developing and maintaining fire test standards are ASTM International (previously the American Society for Testing and Materials) [20] and the National Fire Protection Association (NFPA) [3]. Several fire testing laboratories in the U.S., such as Underwriters' Laboratories (UL) [18] and FM Approvals [13], have established a consensus process that meets the requirements of the American National Standards Institute (ANSI) so that they are permitted to develop and publish American National Standards [21].

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10.3.2.10.4 Future Developments

Currently (January 2020), the regulation for industrial facilities is under revision, but there is no public document available so far.

References for Section 10.3.2.10

[1] Código Técnico de la Edificación. Documento Básico Seguridad en caso de incendio. (CTE DB SI). December 2019.

[2] Real Decreto 2267/2004, de 3 de diciembre, por el que se aprueba el Reglamento de seguridad contra incendios en los establecimientos industriales.

[3] Corrección de errores y erratas del Real Decreto 2267/2004, 3 de diciembre, por el que se aprueba el Reglamento de seguridad contra incendios en los establecimientos industriales.

[4] Real Decreto 842/2002, de 2 de agosto, por el que se aprueba el Reglamento electrotécnico para baja tensión, Published on 18/09/2002.

[5] Ley 38/1999, de 5 de noviembre, de Ordenación de la Edificación, 06/11/1999.

[6] Real Decreto 314/2006 de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación.

[7] Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314, de 17 de marzo.

[8] Nota aclaratoria sobre la aplicación al Reglamento de Seguridad Contra Incendios en los Establecimientos Industriales (Real Decreto 2267/2004) del Reglamento Delegado 2016/364, que establece las clases posibles de reacción al fuego de los cables eléctricos (3 abril 2017).

[9] Garcia Alba, S. Section 10.15 Spain in Plastics Flammability Handbook: Principles, Regulations, Testing, and Approval (3rd Edition), Troitzsch, J. (Ed.), Hanser, 2004.

[10] ENAC website *(www.enac.es)* (accessed January 2020).

10.3.2.11 Switzerland

Marcel Donzé

10.3.2.11.1 Statutory Regulations

According to the federal constitution of Switzerland, the 26 cantons are responsible for matters regarding the public fire authorities, and they enact their own laws. Regarding the "Agreement between all cantons to remove technical barriers to trade" [1], in their laws the cantons have to adopt the fire protection regulation issued by the VKF (Vereinigung Kantonaler Feuerversicherungen, Association of Cantonal Fire Insurances). The intended purpose of this regulation is the safety of people and property in the event of fires and explosions. The regulation consists of the VKF fire protection standard 1-15 [2] and the VKF fire protection guidelines. The fire protection standard specifies the basic principles. Requirements and measures are listed in the guidelines, thematically divided into 19 documents.

10.3.2.11.2 Classification of Reaction to Fire of Building Materials

Within the VKF fire protection regulations, all materials and construction components in buildings with requirements regarding reaction to fire are referred to as building materials. The important criteria for reaction to fire are the burning behavior, smoke production, flaming droplets, and (for cables) corrosivity. Classification is possible according to EN 13501 or a test according to the national VKF guidance "Building material and construction components, part B: Testing regulations" [3].

Classification According to EN 13501

Construction products are classified according to EN 13501. In addition to the reaction-to-fire classification according to EN 13501-1, classifications for roof coverings (according to EN 13501-5) and cables (according to EN 13501-6) apply. In addition, the rules for a "classification without further testing" (CWFT) can also be applied. Details of the tests, the classification procedures and the "CWFT" are described in Section 10.3.1.

Classification According to the National VKF Guidance [3]

The reaction to fire is assessed according to the burning behavior, the degree of smoke development, and the presence of flaming droplets, and is classified by a fire coding. The fire coding is established by standardized tests.

Burning behavior

In the sense used in this assessment, the burning behavior of a material is defined by its flammability and the burning rate, and is substantiated by testing. The classification of building materials is based on combustibility grades 3 to 6. Materials of combustibility grades 1 and 2 are not approved as building materials. Details are shown in Table 10.83.

Table 10.83 Combustibility Grades 1 to 6

Combustibility grade	Burning behavior	Example
1	*Extremely easy to ignite and extremely fast burning*	Nitrocellulose
2	*Easy to ignite and fast burning*	Celluloid
3	*High combustibility* Building materials with high combustibility: burn spontaneously and fast without additional heat supply.	Plastic foams without flame retardants
4	*Average combustibility* Building materials with average combustibility: continue to burn spontaneously for a longer period of time without additional heat supply.	Conditioned white wood
5	*Low combustibility* Building materials with low combustibility: continue to burn slowly or carbonize only with additional heat supply. After removal of the heat source, the flames must go out within a short time interval and afterglowing must cease.	Plastics containing flame retardants
5 (200 °C)	*Low combustibility at 200 °C* Building materials fulfilling the requirements of combustibility grade 5 even under the effect of an elevated ambient temperature of 200 °C.	Rigid PVC
6q	*Quasi non-combustible* Building materials containing a low content of combustible components, which are classified as non-flammable for non-combustible application purposes.	Several mineral wool products
6	*Non-combustible* Building materials without combustible components, which do not ignite, carbonize or incinerate.	Concrete

Determination of combustibility grade

The application of the combustibility grade test described below is normal practice. Special regulations exist for certain materials such as flooring and textile materials.

The test is conducted using a standardized test apparatus shown in Figure 10.42. The test criteria are summarized in Table 10.84.

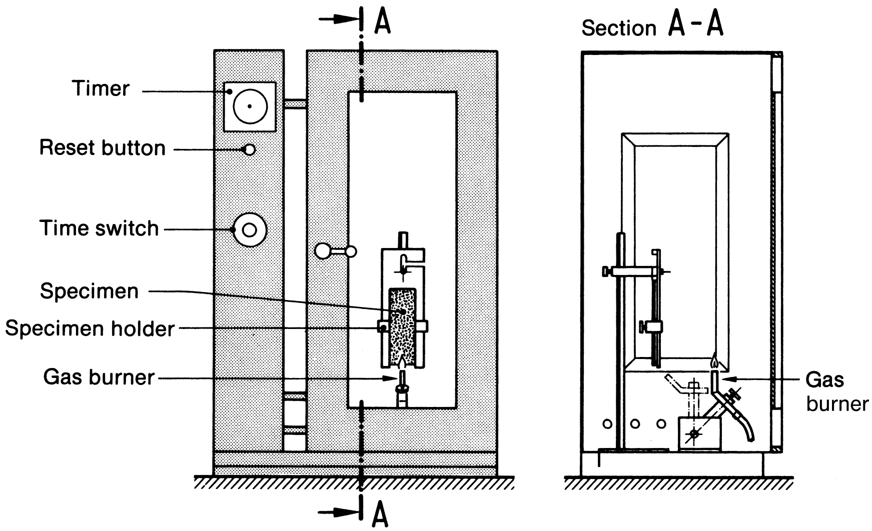

Figure 10.42 Combustibility test apparatus

Table 10.84 Combustibility Test Criteria

Specimens	Six specimens: ▪ Compact materials: 160 mm × 60 mm × 4 mm ▪ Foams: 160 mm × 60 mm × 6 mm
Specimen position	Vertical
Ignition source	Propane-operated displaceable burner, flame tip temperature approx. 900 °C, flame length 20 mm, inclined at 45° to horizontal
Test duration	Flame application 15 s on lower front edge until the flame has reached the upper part of the specimen holder or until extinction
Conclusion	According to test result, classification into combustibility classes 3–5 as specified below

Test procedure at room temperature

A minimum of three tests is conducted. If these three tests do not result in the same classification, the number of tests is increased to six, always deleting the highest and the lowest results. The remaining worst result is the one that determines the classification.

A conditioned specimen of the building material is mounted in a vertical position on the test rig, and a standardized ignition source is applied in the center of the lower front edge.

Test procedure at an ambient temperature of 200 °C

In the test apparatus, which can be heated, the temperature is increased to 200 °C until constant conditions have been reached. The specimen is clamped into the specimen holder. After the specimen has been heated up for 5 min, the tests are conducted as described above.

Classification: The decisive criterion for the classification is the time elapsed from the start of the flame application until the tip of the flame reaches the upper part of the specimen holder (150 mm from the lower edge of the specimen) (referred to as "time") or until the flame extinguishes (referred to as "burning time").

If rising of the tip of the flame to the upper part of the specimen holder is not unambiguously observed, a cotton thread according to the SN 198 898 standard must be tensioned at this level, and the time taken to burn it measured. For classification purposes, the test using the cotton thread has priority over a visual observation. Details of classification and requirements are summarized in Table 10.85.

Table 10.85 Classification of Building Materials Based on Combustibility Test Requirements

Classification	Requirements
Combustibility grade 3	▪ Time to reach upper part of the specimen holder: 5–20 s
Combustibility grade 4	▪ Time to reach upper part of the specimen holder: > 20 s ▪ Burning time: > 20 s
Combustibility grade 5	▪ The flame does not reach the upper part of the specimen holder (150 mm) ▪ Burning time: ≤ 20 s
Combustibility grade 5 (200 °C)	▪ The flame does not reach the upper part of the specimen holder (150 mm) ▪ Burning time at temperature of 200 °C: ≤ 20 s
Combustibility grades 6q and 6	▪ No ignition, incineration, or carbonizing and non-combustibility test

Non-combustibility test

Non-combustibility is tested according to DIN 4102-1 (version 1998), Chapter 5. For details, see Section 10.9.2.1 in the 3rd edition of this Handbook [4].

Classification: The decisive criteria for classification are flame duration, temperature increase in the non-combustibility furnace, and/or level of lower calorific value of the tested building material. Details are shown in Table 10.86.

Table 10.86 Classification of Non-Combustible Building Materials

Classification	Requirements
Combustibility grade 6q	Flaming: ≤ 20 s and Temperature increase (ΔT): ≤ 50 K *or* Calorific value, lower (LHV): ≤ 4200 kJ/kg
Combustibility grade 6	No flaming and Temperature increase (ΔT): ≤ 50 K

Radiant panel test for floor coverings

The combustibility of floor coverings is tested with the radiant panel test. Test apparatus and specifications are based on DIN 4102-14 (version 1990), and are shown in Section 10.9.2.1 in the 3rd edition of this Handbook [4].

The test chamber has a temperature of 18 ± 5 °C. The air throughput rate of the chamber is approx. 170 m^3/h. The incident heat flow radiated from the following distances by the radiant panel onto the plane of the specimen must range between:

- at 200 mm: 0.87 to 0.95 W/cm^2
- at 400 mm: 0.48 to 0.52 W/cm^2
- at 600 mm: 0.22 to 0.26 W/cm^2.

All values from 100 to 900 mm measured for the heat flow – plotted as a function of the distance – result in the heat flow profile required for the assignment of heat flow densities (W/cm^2).

Classification: To specimens which do not ignite (or burn to a width of < 10 cm), a heat flow density of > 1.1 W/cm^2 is assigned.

Specimens burning to a width of more than 90 cm have a lower heat flow density compared to the calibration value at 90 cm. In all other cases, a heat flow density corresponding to the burning distance is assigned to the specimens on the basis of the heat flow density profile.

The value critical for classification is found by averaging the heat flow densities of three specimens (1050 × 250 mm). The classification criteria are summarized in Table 10.87.

Table 10.87 Classification Criteria for Floor Coverings

Classification	Requirements
Combustibility grade 3	Heat flow density: < 0.25 W/cm^2
Combustibility grade 4	Heat flow density: 0.25–0.49 W/cm^2
Combustibility grade 5	Heat flow density: ≥ 0.5 W/cm^2

Smoke-developing behavior

The test is conducted in a standardized test box based on the American XP2 chamber to ASTM D2843. Test apparatus and specifications are described in Section 10.2.1.5. Six specimens are tested, with the required dimensions listed in Table 10.88.

Table 10.88 Dimensions of Test Specimens for Smoke Test (in mm, ±10% tolerance)

	Compact materials	Foams	Composite flooring materials
Length	30	60	30
Width	30	60	30
Thickness	4	25	Original thickness

Three tests are conducted. The specimen is placed on a defined wire netting and is burnt by means of a flame of 150 mm length. Any melting material is exposed to a flame in a metal sheet cup according to DIN 4102-1, item 5.1.2.2 (version 1977). Flame exposure is continued until complete combustion of the specimen.

Classification: The decisive criterion for classification is the maximum light absorption. The requirements are shown in Table 10.89.

Table 10.89 Classification Criteria for Smoke-Developing Behavior

Classification	Requirements
Smoke grade 1	Maximum light absorption: > 90%
Smoke grade 2	Maximum light absorption: > 50 to 90%
Smoke grade 3	Maximum light absorption: 0 to 50%

Fire coding

The combustibility and smoke grades established on the basis of the test results are expressed as “fire coding”, which is a combination of the combustibility and the smoke-developing classification.

For example, a fire coding of 4.1 means that the building material has an average combustibility (grade 4) and develops heavy smoke when burnt (grade 1).

Flaming droplets

A filter paper is placed at the bottom of the test apparatus for the combustibility test. If the filter paper is ignited during the test by a flaming droplet, the product receives the additional assessment “Building material with flaming droplets”.

Reaction to Fire Groups

Based on the reaction-to-fire classification according to EN 13501 or the national VKF guidance, building materials are divided into four reaction to fire groups [acronym = RF (from the French “réaction au feu”)]:

- RF1 (no contribution to fire)
- RF2 (low contribution to fire)
- RF3 (acceptable contribution to fire)
- RF4 (unacceptable contribution to fire).

ences EN 45545-2 as main source – again underlining the importance of this new fire safety standard. It is expected that national developments will be in line with further developments of the EN 45545 series of standards.

11.2.2 Europe

Torben Kempers

For many years, most countries in Europe had their own national railway standards, describing the requirements with respect to fire safety for each country. In these standards, reference was made to the actual application in the railway rolling stock, as well as the operation mode of the train itself. Such standards differentiated between (for instance) commuter trains, high-speed intercity trains, and trains running underground or in tunnels.

With the formation of the European Community and the fact that an increasing number of trains actually cross several borders within Europe, the need for a harmonized railway standard became clear. In 1991, the European Committee for Standardization (Comité Européen de Normalisation, CEN) and the European Committee for Electrotechnical Standardization (CENELEC) joined forces to develop a single series of harmonized European railway standards. This resulted in the publication of the EN 45545 series, "Railway applications – Fire protection on railway vehicles" [1].

The former national standards dealing with the fire protection of railway vehicles have now mostly been withdrawn or are only used for very limited applications within the specific countries (for example refurbishment of old trains or local transportation networks). Therefore, they are no longer dealt with in this section. For the most important countries in Europe (United Kingdom, Germany, France, and others) the national standards can be viewed in the 3rd edition of this book under Section 11.2 [2].

In the following sections, the harmonized EN 45545 series and related standards will be dealt with in more detail.

11.2.2.1 Harmonized Railway Standard EN 45545

Since 1991, the European Committee for Standardization (CEN) has worked on the development of a single harmonized railway standard for Europe. The aim was to replace all existing national standards by one single standard, covering all aspects related to the fire protection on railways. The underlying thought was that such a harmonized standard would support the free trade within the European Union, and become a means to improve the interlinking and interoperability of the national rail networks.

In the following sections, we will explain the development process, the general structure of the standard, the details of the two most important parts, the listed products and requirements, and finally the next steps that are being undertaken.

11.2.2.1.1 Development Process

The actual work to develop the harmonized railway standard has been undertaken within technical committees CEN/TC 256 "Railway applications" and CLC/TC 9X "Electrical and electronic applications for railways", through the creation of a Joint Working Group (JWG). In this JWG various experts from industry, railway operators, and testing institutes joined forces to define the proper test methods and corresponding specification limits.

In parallel, supporting research work was done in projects funded by the European Commission, such as the FIRESTARR ("Fire Standardisation Research in Railways") research project on the reaction-to-fire performance of products in European trains (funded in 1997), and the TRANSFEU project, focusing on the development of a fire safety-performance based design methodology (funded in 2009).

Because of the complexity of the project, it was not until 2009 that CEN/CENELEC decided to publish the harmonized standard, initially as a technical specification, to gather feedback from industry and rail operators. This harmonized set of specifications was the CEN/TS 45545 series, consisting of seven parts.

In April 2010 the draft standard prEN 45545 series was published, for review and comments from the CEN/CENELEC member countries. In total, more than 500 comments were received, which were all addressed by the JWG in a period of 9 months. This resulted in the publishing of the Final Draft FprEN 45545 series in 2012.

Finally, in March 2013 the final version of the EN 45545 series of standards [1] was published. The so-called "date of withdrawal" was set at 3 years, meaning that EN 45545 would become official in March 2016, at the same time replacing all existing national standards.

Amendments to parts 2 and 5 of the series were published in 2015, comprising some minor editorial and technical modifications or clarifications, without changing the overall requirements as listed in the original 2013 editions.

Technical Specification for Interoperability

The EN 45545 is a *voluntary* series of standards. Only after it is referenced in one of the Technical Specifications for Interoperability (TSIs) it becomes mandatory. These TSIs are law in Europe.

The TSI active from 2014, "rolling stock – locomotives and passenger rolling stock" ("TSI–LOC&PAS") [3], referred to EN 45545-2 (from 2013) in the clause regarding "Measures to prevent fire" and the corresponding Appendix J-1 index 58 (material requirements) and 59 (flammable liquids).

This TSI–LOC&PAS also had a clause (7.1.1.5) on "Transitional measure for fire safety requirement". This clause stipulated that during a transitional period ending three years after the date of publication of this TSI (i.e., ending 31 December 2017), it was permitted to still refer to the former regional railway standards – even though they became obsolete with the publication of EN 45545-2. As of 1 January 2018, this transitional measure for fire safety requirement was no longer valid. As of that date, materials for all new projects plus refurbishments (e.g., new parts, designs, or systems) needed to comply with the EN 45545-2 requirements.

The new version of the TSI–LOC&PAS, published in 2019 [4], only allows the application of current EN 45545-2:2013+A1:2015.

11.2.2.1.2 Structure of EN 45545-1 and -2

As mentioned before, the EN 45545 series consists of seven parts:

- Part 1: General
- Part 2: Requirements for fire behaviour of materials and components
- Part 3: Fire resistance requirements for fire barriers
- Part 4: Fire safety requirements for railway rolling stock design
- Part 5: Fire safety requirements for electrical equipment including that of trolley buses, track guided buses and magnetic levitation vehicles
- Part 6: Fire control and management systems
- Part 7: Fire safety requirements for flammable liquid and flammable gas installations.

Of this series, Parts 1 and 2 are the most relevant to plastics in general and their fire behavior in particular, since they describe (amongst others) measures to minimize the possibility of ignition of materials installed on railway vehicles due to accidents or vandalism.

EN 45545-1

Part 1 covers the principal definitions used throughout the whole series, the Operation Categories and Design Categories, the fire safety objectives, and the general requirements for fire protection measures.

Railway vehicles are classified according to four Operation Categories:

- Operation Category 1: Vehicles for operation on infrastructure where railway vehicles may be stopped with minimum delay, and where a safe area can always be reached immediately (example: urban rail)
- Operation Category 2: Vehicles for operation on underground sections, tunnels and/or elevated structures, with side evacuation available, and where there are

stations or rescue stations that offer a place of safety to passengers, reachable within a short running time

- Operation Category 3: Vehicles for operation on underground sections, tunnels and/or elevated structures, with side evacuation available, and where there are stations or rescue stations that offer a place of safety to passengers, reachable within a long running time
- Operation Category 4: Vehicles for operation on underground sections, tunnels and/or elevated structures, without side evacuation available, and where there are stations (example: London Underground).

Note: the boundary between short and long running times is 4 min.

Additionally, railway vehicles are classified under the following Design Categories:

- A: Vehicles forming part of an automatic train having no emergency-trained staff on board
- D: Double-decked vehicles
- S: Sleeping and couchette vehicles
- N: All other vehicles (standard vehicles).

Clause 4 states that the objectives of EN 45545 are to minimize the probability of a fire starting, to control the rate and extent of fire development, and through this, to minimize the impact of the combustion products on passengers and staff. Here the standard distinguishes between fires resulting from accidental ignition or arson, fires resulting from technical defects, and fires resulting from larger ignition models.

Further, EN 45545-1 defines that when vehicles are being maintained and/or repaired, all items replaced shall either comply with the requirements of the EN 45545 series or shall, as a minimum, be of equivalent performance to the item replaced; all parts and components replaced during refurbishment shall comply with the requirements of the EN 45545 series.

EN 45545-2

In EN 45545-2, Hazard Levels (HL1 to HL3) are determined according to Table 11.8, using the definitions on Operation Categories and Design Categories, as given in Part 1.

Table 11.8 Hazard Level Classification

Operation Category	Design Category			
	N	A	D	S
1	HL1	HL1	HL1	HL2
2	HL2	HL2	HL2	HL2
3	HL2	HL2	HL2	HL3
4	HL3	HL3	HL3	HL3

In practice, around 70–90% of the commercial market is covered by HL2.

In EN 45545-2, the essential fire safety requirements are described as follows: “the design of rolling stock and the products used shall incorporate the aim of limiting fire development should an ignition event occur so that an acceptable level of safety is achieved”. The reaction-to-fire performance of materials and components depends on the nature of the base material, but also on the location of the products, their shape and layout, the surface exposed, and the mass plus thickness of the materials. For that reason, all known applications in railway rolling stock have been listed in the table called “Requirements of listed products”, which also includes the corresponding set of requirements that these products need to fulfill. In this table the listed products have been classified and differentiated into subgroups, depending on their general location (interior or exterior) and specific use (e. g. furniture, electrotechnical equipment, mechanical equipment).

For those products that have not been listed in the table “Requirements of listed products” in the standard, one either has to follow the so-called “grouping rules”, or refer to Table 11.9.

Table 11.9 Requirements for Non-Listed Products According to the Exposed Area and Location in The Vehicle

Exposed area	Location	Requirement set
> 0.20 m^2	Interior	**R1**
	Exterior	**R7**
≤ 0.20 m^2	Interior	**R22**
	Exterior	**R23**

In EN 45545-2, some general principles are also given. Specifications apply for (as examples) cables, multilayer laminates, coatings, etc. Noteworthy in this respect is the following principle: *A test which qualifies any product or surface shall also qualify any product or surface which differs in color and/or pattern.*

This principle is different from the one given in the previous national railway standards. In the past the qualification had to be done on each material + color + thickness combination, making the amount of test work very large. This is now no longer required.

In EN 45545-2, the normative Annexes A through D play an important role. For seats, Annex A describes the standard vandalism test for seat coverings, and Annex B is devoted to the fire test method for complete seats.

Annex C describes in detail the test methods for determination of toxic gases from railway products, and Annex D gives the protocol how to prepare the test specimen for the various tests. These Annexes are an integral part of the 2013 version of EN 45545-2, including its Amendment A1 of 2015.

11.2.2.1.3 Requirements

As mentioned before, EN 45545-2 lists a large number of known applications (products) plus their corresponding sets of requirements. In the following section a selection of products and their requirement sets is described.

Wall Claddings, Ceilings, Partition Walls

Products with a relatively large surface area, such as wall claddings and partition walls (IN1A – Interior vertical surfaces) and ceilings (IN1B – Interior horizontal downward-facing surfaces) are linked to the **R1** set of requirements – which is the most stringent requirement set of this standard. Table 11.10 lists the tests that need to be performed and the classification limits for **R1.**

Table 11.10 **R1** Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	*CFE* [kW/m^2]	Minimum	20	20	20
T03.01	Heat Release	ISO 5660-1 at 50 kW/m^2	*MARHE* [kW/m^2]	Maximum	–	90	60
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m^2	$D_{s,4}$ [–]	Maximum	600	300	150
T10.02			VOF_4 [min]	Maximum	1200	600	300
T11.01	Toxicity		CIT_G [–]	Maximum	1.2	0.9	0.75

For these large surfaces both the spread of flame (according to ISO 5658-2 [5]) and the heat release (according to ISO 5660-1 [6]) performance are critical, as are the smoke density and toxicity (both according to ISO 5659-2 [7]).

Strips

When smaller strips of material (IN3A – Strips) are mounted on the walls, the spread of flame performance of the material can still be considered as critical, but the heat release performance no longer is. This is reflected in the **R3** set of requirements, listed in Table 11.11, which does not mention any heat-release requirements.

Table 11.11 **R3** Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	*CFE* [kW/m^2]	Minimum	13	13	13
T03.01	Heat Release	ISO 5660-1 at 50 kW/m^2	*MARHE* [kW/m^2]	Maximum	–	–	–
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m^2	$D_{s,4}$ [–]	Maximum	–	480	240
T10.02			VOF_4 [min]	Maximum	–	960	480
T11.01	Toxicity		CIT_G [–]	Maximum	1.2	0.9	0.75

Seat Shells

When one considers seat shells (F1C – Passenger seat shell – Base, and F1D – Passenger seat shell – Back), it becomes clear that heat release is a critical parameter, but the spread of flame is not. This is because the individual seats are not likely to be able to spread the fire easily. Table 11.12 covers the corresponding **R6** set of requirements, which does not list any spread-of-flame requirements.

Table 11.12 R6 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T02	Spread of Flame	ISO 5658-2	*CFE* [kW/m²]	Minimum	–	–	–
T03.01	Heat Release	ISO 5660-1 at 50 kW/m²	*MARHE* [kW/m²]	Maximum	90	90	60
T10.01	Smoke Density	ISO 5659-2 at 50 kW/m²	$D_{s,4}$ [–]	Maximum	600	300	150
T10.02			VOF_4 [min]	Maximum	1200	600	300
T11.01	Toxicity		CIT_G [–]	Maximum	1.2	0.9	0.75

Electrotechnical Equipment

For most electrotechnical equipment, including connectors, the dimensions and weights are relatively small. Therefore, it does not make sense to focus on spread of flame and/or heat release performance. Instead, for this class of products a different set of requirements has been defined – **R22.** Table 11.13 lists the requirements for **R22.**

Table 11.13 R22 Set of Requirements

Reference	Test	Standard	Parameter	Test criteria	HL1	HL2	HL3
T01	Oxygen Index	ISO 4589-2	*OI* [%]	Minimum	28	28	32
T10.03	Smoke Density	ISO 5659-2 at 25 kW/m²	$D_{s,max}$ [–]	Maximum	600	300	150
T12	Toxicity	NF X 70-100 at 600 °C	CIT_{NLP} [–]	Maximum	1.2	0.9	0.75

In this set of requirements, the Oxygen Index – measured according to ISO 4589-2 [8] – has been listed to characterize the flammability performance of the used material. Spread of flame and heat release are not taken into account.

In this case, the toxicity performance of the material is determined using the French tube furnace test methods NF X 70-100-1 [9] and NF X 70-100-2 [10].

Keywords Index