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Toxicity testing of fire effluents —

Part 1 : General

Essais de toxicité des effluents du feu —
Partie 1 : Généralités

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Contents

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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 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.

The main task of ISO technical committees is to prepare International Standards. In exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the necessary support within the technical committee cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development requiring wider exposure;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standards ("state of the art", for example).

Technical Reports are accepted for publication directly by ISO Council. Technical Reports types 1 and 2 are subject to review within three years of publication, to decide if they can be transformed into International Standards. Technical Reports type 3 do not necessarily have to be reviewed until the data they provide is considered no longer valid or useful.

ISO/TR 9122 was prepared by Technical Committee ISO/TC 92, *Fire tests on building materials, components and structures.*

The reasons which led to the decision to publish this document in the form of a technical Report type 3 are explained in the Introduction.

ISO/TR 9122 will consist of the following parts, under the general title *Toxicity testing of fire effluents*:

— *Part 1: General*

— *Part 2: Guidelines for biological assays to determine acute inhalation toxicity of fire effluents: basic principles, criteria and methodology*

— *Part 3: Methods for analysis of gases and vapours*

— *Part 4: Fire models*

Annexes A and B of this Technical Report are for information only.

Introduction

This Technical Report is intended as useful background information regarding the current state of the art of the development of tests for assessing the toxicity of fire effluents.

It outlines the current philosophy behind the development of tests and indicates how the tests might be used as a contribution in determining the overall toxic hazard, drawing attention to the essential need to take account of information from other fire tests to assess the overall fire hazard.

The report is designed to replace ISO/TR 6543 [1] prepared by an earlier Working Group (WG-12) reporting directly to ISO/TC 92 and published in 1979. The technical report format is retained as being appropriate within ISO for a subject which continues to be under discussion and where the possibility exists of agreement for the preparation of an International Standard at a future date.

The document describes the evolution of thinking on the question of toxic hazards since the publication of the ISO/TR 6543 [1], and attempts to identify clearly those areas where general agreement has been reached and those where divergencies in expert opinions continue to be expressed.

At the time of preparation of this Technical Report, advances are being made within ISO/TC 92/SC3 in identifying the criteria and considering appropriate methods for producing fire atmospheres (fire models), in the biological assessment of toxicity (bioassay methods), in bioanalytical modelling and in analytical techniques for assessing known toxic species in fire gases and laboratory methods.

Considerable emphasis has been directed towards the philosophies expressed within WG-12 of ISO/TC 92 and the more recent WG-4 of ISO/TC 92/SC3. It is recognized that these Working Groups have provided fora for debate by experts nominated by Standards Bodies throughout the world and with international reputations. Knowledge of the differing viewpoints which have been expressed by these experts is essential background to all those who are involved in any way with possible test procedures for assessing the toxicity of fire effluents.

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Toxicity testing of fire effluents —

Part 1: General

1 Scope

The purpose of this part of ISO/TR 9122 is to provide an up-to-date review of the philosophies prevailing on the question of the development of tests for assessing toxic hazards in fire. It presents the state of the art in 1987.

This present report is designed to provide essential information to all those involved with the evaluation of the toxicity of fire effluents not only in the development of meaningful test procedures but also in their use for mitigating hazards.

2 Definitions and abbreviations

For the purposes of this Technical Report, the following definitions apply.

2.1 fire effluent: Total gaseous, particulate or aerosol effluent from combustion or pyrolysis.

2.2 toxicity: Nature (effect) and extent (potency) of adverse effects of a substance upon a living organism.

2.3 toxic hazard: Danger caused to people in fire situations by the formation of toxic products with respect to their nature, quantity, rate of production and concentrations.

2.4 toxic risk: Likelihood that a toxic hazard will occur.

2.5 specific toxicity: Particular adverse effect caused by a toxicant, e.g. narcosis, irritancy.

2.6 toxic potency: Measure of the amount of toxicant required to elicit a specific toxic effect: the smaller the amount required the greater the potency.

2.7 fire model: Means for the decomposition and/or combustion of test specimens under defined conditions to represent (a) known stage(s) of fire in order to generate fire effluents for toxicity assessments. (This term is also used by the fire science community in the mathematical simulation of fire characteristics.)

2.8 pyrolysis: Irreversible chemical decomposition caused by heat, usually without oxidation.

NOTE — This is the 1980 ASTM definition. In the USA, this term is often used to refer to both oxidative and non-oxidative non-flaming conditions when an external heat source is present.

The following abbreviations are used in the text:

Carbon monoxide	CO
Carbon dioxide	CO_2
Oxygen	O_2
Hydrogen chloride	HCl
Water	H_2O
Hydrogen cyanide	HCN

3 General

3.1 Historical background

The toxic effects of exposure to fire effluents were probably observed by prehistoric man on the first attempt to move fire into a cave. The contribution of carbon monoxide to the toxicity of fire effluents has been recognized for more than a century, but it was not until 1951 that an extensive medical-physiological investigation on *The Toxicology of Fire* was reported by Zapp [2]. Animal experiments were directed towards distinguishing quantitatively between the effects of direct flame exposure (skin burns and respiratory burns), generalized heat stress, and toxic factors — including carbon monoxide, carbon dioxide, oxygen depletion, and other toxicants. While carbon monoxide was found to exert the predominant physiological effect in a wide range of natural and synthesized fire effluents, the experiments showed strong evidence of interactions among all chemical and thermal stress factors including simple heat stress.

Rapid expansion of research in polymer science during the 1950's resulted in a substantial growth in chemical and toxicological information relating to fire. A 1963 *Survey of Available Information on the Toxicity of the Combustion and Thermal Decomposition Products of Certain Building Materials under Fire Conditions* [3] listed 297 references. Further expansion of this data base has continued to the present day with major emphasis, from a philosophical point of view, on supplying the fundamental facts upon which any science depends.

In the late 1960's and early 1970's research was increasingly devoted to study of laboratory test methodologies. While fundamental understanding of fire remained as an implicit goal of combustion toxicology, increased emphasis was directed toward attempts to define specific test procedures which might serve to rank, rate, or classify materials with respect to fire safety. Significant studies have been undertaken for example in Germany by Reploh and co-workers [4] and Hofmann and Oettel [5]. A fundamental contribution to the acute inhalation toxicology of combustion products was given by Kimmerle at the 1973 Polymer Series Conferences of the University of Utah [6]. The dual objectives — understanding fire threat and testing materials — were clearly evident in the range of papers presented at the "International Symposium on Toxicology of Combustion Products" held at the University of Utah in 1976. By this time, more than a dozen significant studies had been reported [7] originating in Belgium, France, Germany, F.R., Japan, United Kingdom and United States. The general test philosophy of this period was reviewed by Birky in 1976 [8].

Following publication of the studies noted above, several independent assessments, including one by the US National Academy of Sciences [9], expressed a need to make sure that any projected use of test results should be consistent with an understanding of the shortcomings and limitations of this type of testing. This philosophy has superseded the previously held view that results of toxicity tests could be used directly to provide a ranking order of toxic hazards in fire.

There is also increasing emphasis of the role of toxicological testing as a contributor to hazard analysis/risk assessment for materials rather than as a direct decision-making fire standard. This is consistent with the clear distinction between toxicity and hazard in classical toxicology [10] and is generally embraced by combustion toxicologists, as expressed by Anderson and Alarie in 1978 [11].

Tests were directed in the past to identifying materials which on burning give rise to unusually toxic products[1]. These terms were subject to different interpretations and have been replaced by two more precise terms: products of

- "unusual specific toxicity" which refers to products exerting types of toxic effect not normally encountered in fires (i.e. other than narcosis or irritance); and
- "extreme toxic potency" when the toxicity of the products is much greater on a mass/mass basis than the toxic potency of products usually encountered in fires.

3.2 State of the art reviews of combustion toxicology

An extensive review of the state of the art of combustion toxicology has recently been completed by members of the staff of the Department of Fire Technology at Southwest Research Institute, San Antonio, Texas. Results of this comprehensive study (174 pages) have been published under the title *Combustion Toxicology — Principles and Test Methods* [14]. This document is an expanded version of a report submitted to ASTM Committee E-5 on Fire Standards *A Critical Review of the State of the Art of Combustion Toxicology.* The review of test methods is international in scope and contains extensive comments on advantages and disadvantages of each method as seen by the authors. While the opinions and conclusions presented have not been submitted to consensus processes within either ASTM or ISO, the factual content alone should be very valuable to anyone seeking a better understanding of what can — or cannot — be expected from test data in combustion toxicology.

Another study of similar scope and depth entitled *An Analysis of Current Knowledge in Toxicity of the Products of Combustion* [15] has been recently made available by NFPA (National Fire Protection Association). This study provided background for a summary report from the NFPA Committee on the Toxicity of the Products of Combustion to the NFPA Standards Council.

Both the Southwest Research Institute and the NFPA studies concurred in the conclusions that "the current tests for toxicity of products of combustion are inadequate for regulatory purposes" and "toxicity should be a part of a fire hazard assessment" [16].

3.3 Current position

At the end of 1982, a consensus was reached in WG 4 that there was a need to attempt to integrate toxicity and combustibility information (and not to use toxicity information by itself as a basis for decisions on materials).

No consensus has been reached regarding suitable timing, or, more appropriately, what must be accomplished before it would be wise to propose that a toxicity test procedure be put forward as a Draft International Standard. Despite this there has been agreement that the ISO Working Groups should continue to work towards a DIS dealing with problems as appropriate.

4 Life threat in fire

4.1 General aspects

Although this Technical Report is concerned primarily with the toxic hazards associated with fire, the inability of victims to escape from fire atmospheres is often considered in terms of three major hazard factors:

a) smoke: obscuration of vision;

b) heat;

c) toxic factors: narcosis and irritancy.

Attempts have been made to define the limits of human ability to function and ultimately to survive fires in terms of "tenability limits" for each of the toxic factors (see annex B). It has been suggested that the point at which life or death is determined in a fire is the point at which the first tenability limit is reached. Thus some experimental room fires have been reported in which the tenability limits were reached in a definite sequence and in the order shown above.

However for many fires, there is a considerable question as to the feasibility of dealing precisely with the above factors as separate entities when there is evidence that they usually function in combination.

1) Formerly referred to as "super toxicants".

Thus smoke, which impairs escape ability by obscuration, also contains toxic products which irritate the eyes causing further impairment of vision. Similarly heat stress, severe irritation and narcosis may occur simultaneously in flaming room fires causing profound physical incapacitation, while ultimately the effects of narcotic gases, hypoxia due to oxygen depletion, or heat may cause death.

Thus we can conceive of "toxic hazard" in a general way as that aspect of hazard arising from toxic factors, but it is not at all clear that toxic hazard can ultimately be differentiated quantitatively from overall fire hazard.

In addition the life threat of fire atmospheres is greatly aggravated by special circumstances. Fire is especially hazardous to infants and children, the elderly, invalids, and those whose abilities are impaired by alcohol or drugs. Fire is also a special problem for people in unfamiliar surroundings and in locations where escape is physically blocked or impeded.

4.2 Trends in fire statistics

Fire statistics from the UK covering the years from 1955 to 1971 showed a significant increase in the number of fatal and non-fatal casualties reported as "overcome by toxic gas or smoke". Specifically, Bowes [17] reported a fourfold increase in fatal casualties arising from toxic gas and smoke over that period. Comparable statistics from other countries over these particular years are not available. Historically, however, the UK statistics raised the question of whether the increase in smoke inhalation casualties might have been related to an increased use of modern synthetic materials in furnishings over the same interval.

While fire fatalities attributed to smoke and toxic gases in the UK have continued to increase, the rise has been less dramatic since 1971. Japanese statistics since 1968 and USA statistics since 1977 have not reflected a rise in smoke inhalation fatalities in the recent past.

The early UK statistics, however, have had significant historical impact. There are two views typically advanced in explanation of the 1955 to 1971 UK data:

a) that the composition of fire products has changed so that the smoke from "modern" fires is more toxic on a mass/mass basis than is the smoke produced by "traditional" materials (e.g. wood, wool, cotton), and that the presence of unknown toxicants may account for the fact that persons are now more likely to be overcome and fail to escape from a fire;

b) that the composition and toxicity of fire products has changed little, if at all, but that the rate of fire growth is much more rapid and the rate of evolution of products is much greater than previously.

However in considering these views it should be borne in mind that fire loads may have increased in typical residential living spaces. Also it has been suggested that the statistics may be influenced by changes in the reporting of fires, and that actual fires may not have changed as much as appears.

Information which might be of use in understanding the causes of fire death and injury derive from a number of sources. The information gathered by fire agencies consists mainly of information on the origin and extent of fires and the position of victims, which is of limited use in the understanding of toxic hazard in fires, but when this information is taken in conjunction with data from large scale experimental fires it is possible to make some assessment of effects on fire victims. Other data are derived from pathological studies of fire fatalities [18]. Accounts by fire survivors and the experiences of fire-fighters are promising potential sources of information for understanding the toxic effects of fire atmospheres, although no systematic studies have been published and such information is largely anecdotal.

The main toxic products identified in fires fall into two classes: narcotic gases, which can cause narcosis and death, and irritants which cause incapacitation mainly by effects on the eyes and upper respiratory tract. The latter effect may impair escape capability and sometimes cause death in victims surviving the immediate exposure due to lung damage.

Both of the main narcotic gases known to appear in fires, CO and HCN, have been measured in the blood of both fatal [18] and non-fatal [19] fire casualties. Relatively little is known of exposure to irritant products since these are difficult to identify in the blood as having come from a fire (e.g. HCl, aldehydes). However Treitman et al. and other workers have detected high concentrations of acrolein in some real fire atmospheres [20], [21].

Of the narcotic gases, CO is undoubtedly the most important and produced lethal blood concentrations of carboxyhaemoglobin (> 50 %) in 54 % of fire fatalities in the recent pathology study [18] at Glasgow of the Strathclyde region of Scotland, while some 70 % of victims had carboxyhaemoglobin concentrations capable of causing incapacitation (> 30 % carboxyhaemoglobin), and all the remaining cases except two had burns sufficient to cause death. The contribution of HCN to fire deaths was more difficult to assess since high blood cyanide concentrations were almost always accompanied by high blood carboxyhaemoglobin concentrations in victims, but the blood of 24 % of victims contained sufficient cyanide (> 50 µmol/l) to have had some incapacitative effects and in 5 % of cases to have been life threatening (> 100 µmol/l) [22]. The other major factor associated with fire deaths in this study was a high blood alcohol concentration (42 % of victims), although this factor was found to be less significant in the United Kingdom as a whole.

Some 40 % of fatalities in the Glasgow study had pulmonary haemorrhage which may have been caused by chemical irritants rather than by heat. However, the role of irritants in producing incapacitation in fires is poorly understood, and there is little published human data on the effects of eye and respiratory tract irritance on escape capability, particularly in fires. Combinations of GC-mass spectrometer analysis of combustion product atmospheres with animal exposures are beginning to identify some of the important components [23].

However, another point that emerges from the Glasgow study is that there was no significant group of fatal victims for which death could not be attributed to either CO or burns. There was no evidence that substances of unusual specific toxicity are important in fires, although their existence cannot be ruled out. It must be remembered that although most fatal victims have burns or high blood carboxyhaemoglobin concentrations, this does not prove that either agent was responsible for the initial incapacitation. Nevertheless the evidence from real fires and fire casualties, when taken with data from experimental fire and combustion toxicity studies, suggests that substances of unusual specific toxicity are not important. The major toxic product formed in fires causing incapacitation and subsequent death is CO, with a possible contribution from HCN in some cases [18]. In addition, irritants are likely to play an important part in delaying escape by effects on the eyes and upper respiratory tract and possibly also on the lungs. Also there has been no significant change in the toxicity of fire products that could account for the increased incidence of incapacitation and deaths. The problem in understanding this most probably lies in the way in which the basic products (including carbon monoxide) evolve in modern fires.

4.3 Fire scenarios and victim incapacitation

Data from fire statistics show that the vast majority of fire injuries and deaths occur in domestic dwellings (80 % in both the UK and US) while a small proportion of injuries (20 %) and deaths (10 %) occur in other buildings such as shops, hotels, hospitals and clubs.

There are two different circumstances in which casualties due to toxic combustion products occur, those in the compartment of origin of the fire and those remote from it. In each case the hazards may arise from non-flaming or flaming combustion.

Statistics in the UK indicate that, with fires in domestic premises and in transport fires, most of the casualties occur in the compartment of origin of the fire. For fires in dwellings in the UK this class of fire is responsible for the highest incidence of deaths (60 %) and a high incidence of injuries (39 %) and these fires occur mostly in living rooms or bedrooms and in upholstery or bedding. In these cases the material first ignited may be responsible for the toxic environment, the fire not yet having spread to other materials, there is no thermal flux external to the burning material and the burning or smouldering is sustained by its exothermic nature.

The USA statistics for the years 1980 to 1983 indicate that most of the fatalities from smoke only occur outside the room of fire origin (21 % in the room of fire origin and 77 % outside the room). The reason for this may be linked to differences in the reporting procedures between the UK and USA, due to the inclusion of "joint burn and smoke" victims with "smoke" victims in the UK.

The toxic hazard in such fires depends upon whether there is a long period of smouldering, or whether there is a rapidly growing flaming fire.

With smouldering fires there may be ample time for escape if alerted sufficiently early but persons may be overcome by fumes, particularly carbon monoxide, after a long period of time, if unaware of the danger. It is not possible from fire statistics to determine how common this type of fire is, since in many cases smouldering fires become flaming fires before they are detected. However it is likely that fires which are estimated to have burned for 30 min or more before discovery have involved long-term smouldering and it may be significant that deaths are much more likely in this class of fire.

For flaming fires where the person is in the compartment of origin, the hazard relates to the early stages of fire growth. The most rapidly developing experimental fire takes only a few minutes to reach levels of heat and gases hazardous to life [24], [25].

The inability of persons to escape from such fires seems to depend upon a number of factors. Casualties include a higher proportion of children and old people than does the general population and people who are incapacitated by a previous period of smouldering (see above) or by some other infirmity are obviously more at risk. However there seem to be two other factors of importance, the behaviour of the victim and the exponential rate of fire development.

In many cases there is only a short period during which it is possible to carry out the correct actions enabling escape, after which a person may be rapidly trapped. Some persons may be asleep during this critical escape "window" but there are also reports of situations where the victim was aware of the fire from ignition, but remained to attempt to extinguish the fire or for some other reason failed to attempt to leave before the phase of very rapid fire growth, when heat and CO very quickly reach life-threatening levels.

The second scenario is where casualties occur remote from the source of the fire. Apart from being a common occurrence in domestic dwellings such situations often occur in public buildings where the situation involves a developed fire which has spread from the first ignited material to others. Materials in such fires are subject to substantial external thermal flux and in some cases to oxygen deficient environments. In these cases large quantities of material may be involved in flaming combustion or pyrolysis producing large quantities of toxic smoke and gases.

Fires where the victim is remote from the compartment of origin are responsible for the highest incidence of non-fatal casualties (48 %) in the UK and a large proportion of deaths (37 %). Here the victim is five times more likely to be killed by smoke than by burns and is often unaware of the fire during the crucial early phase, so that the gases may not penetrate to the victim until the fire has reached its rapid growth phase and the victim is already trapped. The major causes of incapacitation and death in this type of fire are almost certainly fumes, particularly carbon monoxide, which can build up rapidly to high concentrations and the role of irritants in causing incapacitation and impeding escape attempts may be crucial.

5 Chemical nature of fire effluents

5.1 Mechanisms of product formation

Knowledge of the main routes leading to the formation of combustion products [25], [26], [27] is an essential part of the wider understanding of the chemical aspects of combustion toxicology of fires.

Under the action of heat, organic polymeric materials decompose and release volatile products. If a sufficient concentration of these products is attained and ignited then a flame may develop and feed back to the polymer to continue the process.

The primary step in product formation therefore involves the thermal decomposition of the polymeric material and may take place in fires over a wide temperature range in oxidative or inert (pyrolytic) conditions. Most of the chemical products present in fire atmospheres are species which have been produced from the decomposition of polymeric materials and which have escaped flame destruction. At relatively low temperatures (up to about 400 °C) a polymeric material decomposes to give a restricted number of complex chemical products. It is at medium temperatures (400 °C to 700 °C) that the greatest variety and often the greatest quantities of products, which may include hydrocarbons, oxygenated species (aldehydes, ketones), etc., are produced. This is also the main region where polymers which are sensitive to oxygen may form oxygenated species by incorporation of atmospheric oxygen.

At high temperatures (in excess of about 700 °C), organic and organometallic compounds which are unstable under the normal contact times achieved under these conditions may decompose. Also present are complex polycyclic hydrocarbons and other stable products of low molecular weight such as hydrogen cyanide and certain organic nitriles. By contrast, combustion with flame tends to destroy these products with the formation of a small range of simple combustion products. For example, with a polymer containing carbon, hydrogen and oxygen, the combustion products will be carbon monoxide, carbon dioxide and water; if nitrogen is also present, then molecular nitrogen and oxides of nitrogen may also be formed.

In addition to CO, CO_2 and H_2O, a wide variety of products are formed in fire effluents. For example, the chemical species produced during the burning of wood and polypropylene (40 kg) in a room-corridor are shown in table 1. Also shown is a summary of the main chemical groups.

5.2 Characterization of fire atmospheres

During recent years, major advances have been made in the analysis of fire effluents [27]. It is recognised that the overall nature of the products is dependent particularly upon the type of polymeric material, temperatures and ventilation conditions. A number of factors are important in defining fire atmospheres both for toxicological considerations and in comparing atmospheres between laboratory and full scale fire studies.

These factors include

a) the yields of oxides of carbon (and CO_2/CO ratio) and reduction in oxygen as a measure of the basic combustion conditions;

b) the concentration of additional specific toxic gases (in relation to carbon monoxide) which may be important for the specific polymers burnt (e.g. hydrogen cyanide, hydrogen chloride);

c) types and concentrations of "unburnt" organic products (chemical fingerprints) including:

1) total concentrations relative to carbon monoxide,

2) percentage distribution of important groups, e.g. aromatic and aliphatic hydrocarbons, oxygenated species, amines, nitriles, halides, etc.;

d) rate of production of total quantities of the major products of toxicological significance.

Other important aspects regarding the fire effluent include

a) obscuration (usually optical density per metre), rate of production and total amount of smoke produced;

b) temperature of the effluent and radiation from the effluent.

5.3 Classification of fires

Recent research has shown that in spite of the enormous complexity of fire effluents, the oxygen concentration and the relative concentrations of carbon dioxide and carbon monoxide (CO_2/CO ratio) can provide a simple means of characterization. This arises because the relative conversion of oxygen to carbon monoxide and carbon dioxide depends markedly on the oxygen concentration, with high oxygen concentrations favouring complete combustion to carbon dioxide and conversely restricted oxygen giving rise to carbon monoxide.

By combining CO_2/CO ratios with oxygen concentration and expected fire "severity" as based on expected temperatures (or irradiance), a number of different fire types can be classified, as summarized in table 2. These fire types are:

1 a) Smouldering (self-sustained)

Although often misunderstood, smouldering is generally defined as a self-sustaining exothermic decomposition sometimes accompanied by glowing. Smouldering is initiated by a local high temperature source in the absence of area heating. It takes place mostly in natural materials and some synthetic-natural composites, involving a smouldering front which propagates across the material (as in cotton, fibreboard) or within a bulk (e.g. polyurethane initiated by smouldering cotton). Since complex balances between heat generation and loss are involved, particularly with bulk materials, the phenomenon is not always easy to produce.

Local temperatures at the smouldering front may range from about 400 °C (polyurethane foam) to 800 °C (cotton) and in some cases considerably higher. Oxygen concentrations near to the front may be below ambient but the overall demand on oxygen is low and long periods usually elapse before surrounding oxygen concentrations fall significantly. Smouldering will often continue in closed surroundings to a few percent oxygen. Since the condition is essentially a non-flaming one, CO_2/CO ratios have little significance. Temperatures of the general environment rarely exceed around 100 °C.

The phenomenon of smouldering is important as a process which continues to lead to loss of life, with early types of furniture and beds/bedding set into smouldering from sources such as smoker's materials. In the room of fire origin, carbon monoxide concentrations may be of the order of 0 ppm to 1 500 ppm with irritants present. The time to incapacitation is often long (hours rather than a few minutes) usually with ample time for escape if alerted.

1 b) Non-flaming (oxidative) decomposition

During fires and related circumstances (e.g. overheating), materials and composites can be heated under conditions where ample oxygen exists and toxic decomposition products can be formed. Examples include the radiative transfer of heat from a fire plume to remotely sited materials during the growth phase of fire before flashover has occurred, the heating of lining, flooring or ceiling materials by heat conduction through building structures and bulkhead etc., and general overheat situations (electrical cables, electrical/electronic components particularly where outer surfaces become very hot). Oxygen concentrations in the vicinity of such conditions may be 21 % or reduced to about 5 % (still significant in oxidation terms). CO_2/CO has no significance since flaming is not involved. Since the condition is only relevant under pre-flame conditions, the direct temperature of materials and composites will normally be less than 500 °C, as otherwise auto-ignition will occur for flammable materials. Similarly where the condition is induced by heat radiation, pre-flashover conditions will usually mean irradiances less than 25 kW/m^2.

Oxidative decomposition has an external heat source and therefore is not self-sustaining. It should not be confused with smouldering.

1 c) Non-flaming (pyrolytic) decomposition

Item 1 b) above is related to oxidative decomposition of materials by, for example, heat radiation or overheat conditions. In some cases oxygen concentrations in the vicinity of the material may be insufficient to induce oxidative decomposition. Under these conditions (usually less than 5 % oxygen) the decomposition will be "pyrolytic". Examples include the overheating of material such as insulation in cavities where there is limited oxygen availability but where there are passageways for release of toxic products to other parts of a building or transport complex and the overheating of cables where interior materials are protected from the atmosphere.

Under these conditions temperatures as high as 1 000 °C may be involved since ignition cannot take place even with flammable materials. Since there is no flaming the CO_2/CO ratio is not relevant. Normally this condition cannot be achieved by heat radiation.

2 Developing fire (flaming)

During the early stages of flaming fires (pre-flashover), materials and composites are decomposed primarily by the increasing feedback of heat radiation from the flame. The overall environment is a complex one, since there is a "micro-environment" where materials are at elevated temperatures in the immediate vicinity of the flame, together with a more general environment where materials etc., are being heated by a growing irradiance from the flame. In rooms which reach flashover with temperatures between 400 °C and 650 °C, the effective blackbody radiation is in the range 20 kW/m^2 to 40 kW/m^2.

Experience shows that CO_2/CO ratios are typically 100 to 200, with oxygen concentrations of down to about 15 % or 10 %. Carbon monoxide concentrations may typically reach 1 % with CO_2 up to 10 % at 10 % to 15 % oxygen. In combination with the irritants, smoke and heat, persons in the room of origin may have a few minutes to incapacitation.

3 a) Fully developed flaming fires (low ventilation)

The severity of fully developed fires is dependent markedly on the available ventilation. Where ventilation restricts development in post-flashover fires, oxygen concentrations may fall as low as a few percent and CO_2/CO ratios reach values less than 10. Typical irradiance will exceed 40 kW/m^2 (temperature > 600 °C).

3 b) Fully developed flaming fires (well ventilated)

Under well ventilated conditions where there is little restriction on the oxygen available to the fire, typical irradiances will exceed 50 kW/m^2 up to as high as 150 kW/m^2 (material temperature 600 °C to 1 200 °C); CO_2/CO ratios will normally be less than 100 with oxygen concentrations less than 10 % (typically 5 % to 10 %).

Under fully developed fire conditions, persons in the vicinity of the fire may experience concentrations of carbon monoxide (up to about 3 %), hydrogen cyanide (up to about 500 ppm), irritants, smoke and some heat. Cooling may have given breatheable temperatures of fire gases. Under these conditions, time to incapacitation may be much less than a minute.

6 Experimental fire studies

6.1 General aspects

After ignition, fire development may occur in different ways, depending on the environmental conditions as well as on the arrangement of fuel. However a general pattern can be established for the fire development. In the case of a compartment fire, the general temperature-time curve shows three stages (see figure 1).

Stage 1 represents an exponential rise of the fire room temperature, when there is enough oxygen present (developing fire). A second stage is reached when the surface of all combustible contents of the room will be decomposed to such an extent that sudden ignition occurs all over the room (flashover); this characterizes the stage of the fully developed fire. In this stage 2 (fully developed), the rapid temperature rise of flashover is subsequently moderated by oxygen depletion to a steady state (often termed ventilation controlled).

In stage 3 the combustibles in the room are depleted and the temperature decreases depending on the ventilation and the heat- and mass-transfer relations.

In each of these phases, a different mixture of decomposition products will be obtained. In order to study a material's contribution to a fire atmosphere, consideration of the production of fire effluents from the material under different conditions of both temperature and ventilation is necessary. Moreover information is required of the fire situation being considered. In this way, one can seek to derive the yield of effluent per unit mass decomposed, which together with the mass involved in the fire gives an estimation of the material's contribution.

6.2 Results of fire simulation tests

A number of fire tests have been reported in the literature to study the behaviour of materials and composites under simulated full scale conditions. Many of these have involved the contents of buildings rather than components, reflecting the view over recent years that it is often the contents of buildings which are first ignited and produce the initial life threat in fire.

In 1978 tests were carried out with furniture [28] arrangements simulating the stacks of furniture involved in the Woolworths Store fire in Manchester. In 1981 tests included a simulation of the Dublin "Stardust" Disco Fire [29].

Fires in fully furnished rooms have been studied by the US Southwest Research Institute [14], the International Isocyanate Institute at the Moreton-in-Marsh facilities in the UK [30] and the US National Bureau of Standards [54]. Room burns were also studied by the Technical University of Clausthal-Zellerfeld (Jeschar, Ehlert) [31].

For building components, large scale studies have often included corner wall tests. An example is the work of Chien, Nadeau and Waszeciak [32] in 1981 on cellular plastics.

The results of these tests and others [33] to [45] have provided a valuable insight into the concentrations and spread of combustion products and the importance of ventilation, building construction and fire load.

Overall the results have borne out general conclusions drawn by Armstrong [46] :

a) the major hazards of a fire are more related to the fact that a fire exists at all than to the material involved;

b) with few exceptions, where potentially serious concentrations of, for example, HCN have been detected, they have occurred after smoke, heat or CO have already created a questionable life support atmosphere.

As discussed earlier in this Technical Report, a useful classification for studies of fires can be based on the types, temperature rise, oxygen concentrations and CO_2/CO ratio as summarized in table 2.

It is interesting to note that when the CO_2/CO ratio is plotted against the oxygen concentration for steady-state burning phases of various room fire simulation tests carried out at three different laboratories, there is a general scattering of results as shown in figure 2. This suggests that the CO_2/CO ratio is a characteristic of the fire conditions employed by each laboratory rather than that of the materials being burnt.

It is important therefore that the experimental laboratory fires are defined carefully including particularly ignition source (type, intensity, duration), fire load (composition, geometry of mass distribution), room size and ventilation (openings).

7 Toxicity testing of fire effluents

7.1 Introduction

Fire effluents consist of a complex mixture of solid particulates, liquid aerosols, gases and vapours. Although fires may generate a wide variety of effluents, toxicity tests have shown that gases and vapours are a major factor causing acute toxic effects. The predominant effects may be separated into three classes: narcosis, sensory and/or pulmonary irritation, and those effects representing other or unusual specific toxicity.

Although bioassay methodology varies depending upon the class of toxicant, most test methods follow the same general plan. One of a number of combustion methods chosen to represent certain real-fire conditions is selected to produce fire effluents by burning or thermally decomposing a material. The effluents are presented to animal subjects, usually rodents, which are exposed for a specific period of time with certain biological response end points being observed.

The responses most commonly employed for narcosis are lethality and incapacitation, with the latter defined as inability to perform either a conditioned response or some normal motor pattern. Assessment of the effects of irritants in fire effluents is more complex. Such toxicants do not immobilize persons at concentrations which result in death after the exposure. Moreover, within-test end points for irritants in rodents have not been demonstrated to have quantitative correlation with human response; however, post-exposure lethality is used to assess pulmonary irritant effects. Fire effluents possessing other or unusual specific toxicity are normally assessed through clinical examination of exposed animals.

In general, biological responses are related both to the concentration of the toxicant and to the length of the exposure time, with the product of concentration × time (*Ct*) being a quantitative expression of the insult to which a subject is exposed. This "exposure-dose" is assumed to be proportional to the actual dose retained by the subject. The *Ct* "exposure-dose" required to produce a biological effect is, to a first approximation, reasonably constant over the range of concentrations of toxicants of interest in fires. An exception to these generalizations is sensory irritation which is primarily related to concentration, rather than to "exposure-dose".

Toxicity has both qualitative and quantitative aspects. In evaluating quantitative aspects, a concentration-response relationship may be determined by measuring the response of animals exposed over a fixed time to different concentrations of a fire effluent. This is accomplished by conducting a series of experiments in which the quantity of material combusted or the flow rate of diluting air is varied in order to produce different concentrations of the fire effluent. The number of animals showing a response, either as lethality or as incapacitation, will increase as the exposure concentration is increased. When the percentage of animals responding within a specified time is plotted as a function of logarithm of the concentration, a straight line is typically approximated over a limited range. Statistical methods are employed to determine the concentration required to produce a specified effect. The concentration which will produce a response or effect in 50 % of the animals within the specified time can be obtained by interpolation. This effective concentration is commonly termed the EC_{50}. The EC_{50} is a general term and may be used for any observed response of the animal. When lethality is the observed response, the term LC_{50} is used to denote the concentration of material or fire effluent that produces death in 50 % of the animals for a specified exposure time. Similarly, the IC_{50} designates the concentration necessary to incapacitate 50 % of the animals also for a specified exposure time.

Some test methods measure the rapidity of action of the fire effluent in causing either lethality or incapacitation. In these methods, concentration is held constant and the times at which animals die or are incapacitated are recorded. From these data, a mean time-to-death (LT_{50}) or time-to-incapacitation (IT_{50}) is determined to characterize the toxic potency of the smoke.

All of these terms (EC_{50}, LC_{50}, IT_{50}, IC_{50}, etc.) can be used to characterize the toxic potency of fire effluents.

7.2 Review of some typical test methods

There are at least seven test methods which have been widely considered for assessing the toxicity of fire effluents. Several additional methods have also been used to some extent and are currently under review within ISO/TC 92/SC 3/WG 1. These additional methods will not be referenced here but include those referred to as USSR, Japanese, British, NASA, Allied Corporation, Israeli, Canadian and SRI International methods.

However, those referred to as the DIN, CAMI, NBS, US-Rad, U-PITT, JGBR and USF methods have all been used with a sufficient number of materials as to achieve some significant level of attention in the combustion toxicology literature. The characteristic features [14] of each of the methods are summarized in table 3, along with the following brief descriptions.

The DIN 53436 (Deutsches Institut für Normung, Germany, F.R.) [47] specifies the combustion apparatus and the operating procedure. The description of the animal response model is designated as a draft. The method is characterized by the use of a moving annular tube furnace operated at a constant temperature with fire effluents being diluted with air before rats are exposed. Fire effluents are generated dynamically, i.e. continuously over the exposure time of the animals. Concentration-response relationships are easily obtainable, with concentration being varied by dilution of the fire effluent with air.

A method in use by the CAMI (Civil Aero-Medical Institute) of the FAA (US-Federal Aviation Administration) [48], uses a tube furnace operated in a static model (with recirculation) at a constant temperature. Times to incapacitation and death for rats exposed in motor-driven rotary cages serve as end points.

The NBS test (US-National Bureau of Standards) [49] is a static system using a cup-type furnace as the combustion device, operated just below and just above the auto-ignition temperature of the specimen. Concentration-response relationships are determined using rats, with concentration being controlled by varying sample mass.

The US-Rad (Radiant Furnace Test) uses the same exposure chamber as the NBS test providing a static animal exposure system. Animal exposures are controlled by varying the irradiation intensity and duration and are quantified in terms of concentration × time products. Rats are used only after preliminary tests evaluating the relative concentrations of known toxicants are conducted.

The U-PITT methodology (US-University of Pittsburgh) [14] exposes mice to fire effluents produced in a dynamic system from programmed heating of a specimen in a box or muffle furnace. Bioassays include concentration-response and time-to-death for lethality and respiratory rate depression for assessment of irritants.

The JGBR (Japanese Government Building Regulation Toxicity Test) (1976) includes a test method [51] using a radiant heat furnace (modified UK BS 476-6, *Fire Propagation Test*) and exposes mice to smoke produced in a dynamic system from programmed heating of the specimen. Incapacitation times of eight mice that are placed in rotary cages are determined. Incapacitation times are compared with those of the reference material (a defined wood).

The USF method (US-University of San Francisco) [14] is also known as the Dome Chamber Method. Mice are exposed in a small dome-shaped chamber to fire effluents produced from a tube furnace using either constant or programmed heating. Although concentration-response relationships can be determined by varying sample mass, most data involve time to various degrees of incapacitation and also death.

Similarities and differences among these methods are notable. Three of the seven methods (DIN, CAMI and USF) use a tube furnace as the combustion device, with the NBS method using a cup furnace or, in a modification the US-Rad, a radiant heat device, as does the JGBR method. The U-PITT uses a box or muffle furnace. Most combustion furnaces are operated at fixed temperatures or heat fluxes, except for the U-PITT method in which heating is programmed. Modifications of the USF and CAMI methods also enable programmed heating. Fire effluents are diluted with air in both the DIN and U-PITT methods and optionally, in the USF method. The static mode is used in the CAMI and NBS tests.

The U-PITT, JGBR and USF methods use mice as the test animals, whereas the others use rats. Animals are exposed to fire effluents for 30 min in most of the procedures. In four of the methods, animals are restrained for exposure in the head-only mode, three methods use whole-body exposures and in the DIN method, animals may be exposed in either mode.

Concentration-response relationships and LC_{50} values may be determined in all of the test methods. The DIN, CAMI and USF methods also commonly utilize time-to-effect end points. In the normal operation of the CAMI and USF methods, a fixed quantity of material is decomposed and time-to-incapacitation (t_i) and time-to-death (t_d) values are measured. In the DIN, NBS and US-Rad methods, lethality is the principal end point. Additional physiological end points, such as respiratory rate depression, may be measured in the U-PITT method.

The seven test methods do not differ greatly in the chemical analyses included in the procedures. Each method normally employs measurement of CO, CO_2 and O_2. Additional selected gases, principally HCN and HCl, are optionally measured by most of the methods. Measurement of blood COHb saturation levels of exposed animals is routinely made by only two methods, the DIN and the NBS test.

7.3 Limitations of laboratory smoke toxicity tests

All laboratory test methods suffer from several types of limitations. Due to rapidly changing conditions in a real fire involving the dynamics of fuel, heat and air interactions, it is unrealistic to expect that a single laboratory test will be relevant to all stages of all fires.

However, all the tests might be expected to be relatable to at least some stages of actual fires. This has been shown in certain cases [5]. Each laboratory combustion device also presents certain physical limitations with regard to specimen size, shape or assembly. The NBS cup furnace is, for example, admitted to be inappropriate for composites, laminates, etc., [14]. Furthermore all of toxicology is plagued with the question of the relevance of test animals to exposure of humans. In the case of the common asphyxiant carbon monoxide, the rodent is considered a reasonable model, with animal responses being fairly predictive of toxicological effects in humans. With other toxicants, such as irritant gases, caution must be exercised in extrapolation of laboratory data obtained with rodents to predict effects in humans until such time as quantitative correlations can be adequately studied.

In general, laboratory fire effluent toxicity tests are unable to demonstrate practical quantitative differences between most materials — differences which can be used with confidence for choosing one material over another in the interest of improving fire safety. Experience has shown that most common materials, both natural and synthetic, do not differ widely in the toxicity of fire effluents produced from combustion. Some of the differences observed, though even of statistical significance, are of questionable practical significance from the viewpoint of impact on hazard to life safety in a fire. There are, however, a very few cases of toxic potency found to be greater than the normal spectrum exhibited by most materials. Identification of such a situation appropriately causes the producers of these materials to seek additional performance information for purposes of responsible development and application of their products.

7.4 Analytical methods as alternative to animal testing

The role of testing could be basically to confirm that the toxicity of a fire effluent atmosphere can be adequately described by a consideration of the known constituents and that no other toxicants are present in toxicologically significant amounts.

As a result of considerable research on the common fire effluent toxicants, concentration-time-response mathematical relationships are now becoming well understood. Effects of the narcosis-producing toxicants, CO and HCN, on rats, along with reasonable extrapolation to humans via non-human primate studies, can be predicted from analytical determination of the time course of toxicant evolution. Combined effects for CO and HCN cannot yet be predicted with certainty, although current research is aimed at answering questions of any interaction. In addition, concentration-time-response relationships for irritant combustion products (HCl, in particular) are now being worked out to enable prediction of irritant effects from analytical data.

It thus appears likely that assessment of both incapacitation and lethal effects of fire effluents containing the common toxicants will not require the use of live animal models on a routine basis for determination of IC_{50}'s or LC_{50}'s. The role of a toxicity test using animals would be primarily to validate effects predicted from mathematical models, to detect unusual specific toxicity and to assess irritation. Assessment of the latter two effects cannot be accomplished from chemical analysis [52].

8 Hazard analysis/risk assessment

8.1 General aspects

As discussed in clause 4 on life threats in fire, it is not widely recognized that fire threats are highly interactive and that a valid assessment of the hazard or risk of materials in fire requires some system of integrating combustibility properties with other aspects such as obscuration of vision and toxicological factors.

The term "hazard analysis" implies a descriptive study of circumstances and events that can threaten life or health. "Risk assessment" implies an attempt to make a more quantitative evaluation of one or more of the hazards described.

In fire safety, procedures of risk assessment might be applied to situations or applied to materials (including various manufactured products). These two approaches are not totally different; they differ only in emphasis.

In the assessment of risk both the fire situation (or scenario) and the materials are necessary considerations.

Studies emphasizing co-ordinated application of fire safety measures to entire situations or systems will probably be the most productive of overall safety gains. There is, however, considerable interest in the limited objective of improving our methods of comparing and specifying materials or manufactured products.

8.2 Approaches to fire risk assessment

There are at least three general approaches to fire risk assessment which have been either used or commonly suggested.

8.2.1 End-use simulation fire tests

These are usually considered as large-scale tests, although smaller scale testing can be used in some end-use simulations as in the study of cigarette ignition of upholstered furniture. The basic philosophy is that it is not necessary to quantify all of the interactive fire variables if they are allowed to function in a test fire which closely simulates the circumstances of accidental fire. The development of smoke, heat and toxic products is closely monitored. Test animals have been used for integrating various aspects of hazard, but chemical and thermal profiles often provide much of the information that is needed.

8.2.2 Mathematical modelling of fire

Mathematical modelling of fire growth coupled with smoke and toxicological data could provide an integrated risk assessment procedure for comparing alternative materials or situations. Once developed, this type of modelling should permit many comparisons to be made at minimal cost. The objective is widely recognized, and research on fire modelling is underway at several locations.

8.2.3 Combination of weighted numbers from fire tests

This approach has been suggested for comparing materials in overall fire-safety merit. Generally, it is proposed that small-scale test data be gathered related to various aspects of fire behaviour such as combustibility, smoke and toxicity of combustion products. Weighting factors are then applied to the various test numbers and the results are combined by addition or multiplication. Although this reduces the data to one result, there are problems. It is not easy to get consensus on what tests should be used and how the results should be weighted and combined. More importantly, this process is not a functional model of nature and interactions between factors are not handled. Still, this approach could easily be an improvement over listing the same test data as separate pass-fail criteria.

8.3 Toxic hazard

In view of the interactive nature of fire threats, it is not clear whether or not toxic hazard can be quantified as "toxic risk" independent of other fire risks. Nevertheless, a considerable background of philosophy has been developed regarding the toxicological aspects of fire hazard and risk [53].

The toxic threat posed by a fire effluent depends upon the relationship between the time taken for an untenable environment to be generated and the time taken for the threatened population to escape to a place of safety. The toxicity of the environment is determined by the chemical composition, concentration, and physical state of the effluents and duration of exposure.

8.3.1 Chemical composition

The chemical composition of the effluent products from a fire is affected by the temperature and concentration of gases, particularly oxygen, in the micro-environment of the combustion zone. For this reason, the shape or orientation of a burning component, the incident thermal flux, oxygen availability, etc., all affect not only the rate of generation of combustion and decomposition products but also the chemical composition of those products. For example carbon monoxide may be the predominant product in oxygen-deficient circumstances, but carbon dioxide the principal product under ventilated conditions; or with nitrogen-containing organic compounds, hydrogen cyanide may predominate where high thermal fluxes are present, but other nitrogen-containing products may be the main product where the thermal flux is lower.

8.3.2 Concentration

The concentration of a fire effluent is a function of the rate of generation of the substance, its rate of dissipation, the volume in which it is contained and, if there is insufficient material for a steady state to be reached, the duration of the fire.

8.3.3 Physical state

In order for an airborne substance to exert its toxic effect, it must gain entry to the respiratory tract. This is dependent upon the physical form of the substance, i.e. a gas, volatilized liquid or suspension of liquid or solid. For suspensions, the particle size has a major influence on uptake and site of deposition in the respiratory tract.

8.3.4 Assessment

Provided that the appropriate fire model is used, the rate of generation of toxic species could be assessed for the individual common toxic gases by analytical chemical methods and in the simplest approach the results would be employed in appropriate formulae. To assess other effects such as synergism and to consider the whole range of fire products, results derived from animal tests would be necessary.

Toxic hazard assessment would utilize these data in considering each fire environment including those mitigating actions described in 8.4.

8.4 Mitigation of hazard

The principal hazard depends upon a rapid spread of fire in the material first ignited and since it may be assumed that all organic material will give rise to carbon monoxide and smoke when burning, mitigation is best approached through improving resistance to ignition and control of combustion rate of the systems concerned. For this purpose the properties of ignitability and rate of combustion should be measured in the absence of a thermal flux external to the system and control of these two parameters be considered the most significant initial approach to the reduction of this hazard.

The associated smouldering hazard, since it is concerned with an immobile victim, is not critically dependent on the rate of generation of toxic products. Eliminating the possibility of a system smouldering when subjected to a small ignition source should be the first approach to reducing the hazard in these circumstances. There is also a need to ensure that no materials with unusual specific toxicity are generated during smouldering combustion: the determination of this depends upon a toxicity test in the smouldering mode and in the absence of an external heat flux. Hazards can of course be mitigated by other appropriate means such as smoke/heat detectors.

The hazard remote from the source of fire does depend on the rate, quantity and toxicity of fire effluent products arising in the developed fire. Mitigation here depends on the control of the properties of systems, particularly toxicity, rate of fire growth and generation of toxic species. Additionally escape times from the fire zone depend on control methods such as smoke extraction and management, sprinklers and compartmentation.

Ignitability and overall flammability may be the prime considerations in reducing toxic hazard.

9 Concluding remarks

This report has attempted to put forward the current state of the art regarding the understanding of the toxicity of fire effluents and in the development of test methods.

Great emphasis has been directed towards the considerable concern which has been expressed by experts in the Working Groups about the need to address the problem of toxic hazard rather than toxicity *per se*.

The report has been prepared in parallel with other Working Groups in ISO/TC 92/SC3 considering bioassay methods, fire models, analytical methods and bioanalytical modelling.

In spite of the growing concern being voiced about the future use of animals in routine test procedures, there is a recognition in this Technical Report that information derived from analytical methods cannot fully predict the possible toxicological effects of fire effluents. However the use of tests which minimize the use of animals is strongly encouraged.

Support is therefore given both to the continuing development of satisfactory fire models and also to biological methods for assessing the toxicity of fire effluents to provide specific information about toxicity providing that the results of such evaluations form part of an overall consideration of hazard and consequently the mitigation of that hazard.

Toxicity should not be confused with toxic hazard and information derived from a toxicity test (based on a simple fire model) may be very limited in application to hazard.

Table 1 — Example of the yields of fingerprint compounds at three stages of fire (flaming combustion)

Values in parts per million

Wood: Compound	Growth	Steady State	Decay
Methane	11,9	96	7,9
Acetylene	0,8	35,8	5,7
Ethylene	1,9	22,2	9
Ethane	0,2	0,3	
Allene		1)	
Propene	5,7	104	10
Cyclopropane	0,1		
Propyne	0,6	22,3	1,1
Methanol	3,7	329	34,1
Acetaldehyde	7,2	65	1,6
Butene, Butadiene	1,3	90,7	1
Ethanol		0,2	1)
Acrolein	2,7	3,7	1)
Acetone	2,7	269	52,1
Cyclopentadiene	2,5	248	48,1
Crotonaldehyde		6,3	1)
Hexene/Cyclohexane	1)	2,4	6
Benzene	1,8	603	153
Cyclohexadiene	1)	1)	
Heptene	0,1	1)	
Heptyne	0,1	1)	
Heptadiene	0,2	1)	
Toluene	0,5	182	20,4
Octene	0,5	3,6	2,3
Xylene	0,8	28,6	5,1
Styrene	0,5	72	3
Nonene	0,3		
Benzaldehyde	3	95	60
Methyl styrene	0,3	23,4	1)
Decene	0,3		
Indene	0,7	85	8,2
Ethyl styrene	1,6	12,2	1)
Methyl indene	1)	19,6	
Naphthalene	2,2	164	

Polypropylene: Compound	Growth	Steady State	Decay
Methane	0,2	1)	1)
Acetylene	2,8	0,6	1,2
Ethylene	2,4	2 020	900
Ethane	5,1	980	350
Propene	3,3	31,2	3,7
Propyne	1)	25,7	6,2
Methanol	0,5	6,2	12,7
Acetaldehyde	2,7	3,9	2,5
Butene, Butadiene	0,5	18,3	3,1
Cyclobutane		1)	1)
Butane	1)	0,7	0,1
Ethanol			1,7
Acrolein	1)	1)	7
Acetone	900	216	32,5
Cyclopentadiene		23,9	1,1
Pentadiene	1)	1)	1)
Crotonaldehyde	17,2	5,4	7,3
Hexene	0,3	0,4	0,1
Benzene	72	810	575
Cyclohexadiene	0,5	0,1	1)
Heptene	1,2	1)	
Toluene	54,5	56,5	31,6
Octene	1,6	0,4	0,6
Octadiene	1)	0,2	0,1
Xylene	43	26,5	15,1
Styrene		32,2	5,6
Nonene	3,1		
Benzaldehyde, Methyl styrene	12,5	10,7	12,3
Indene	0,4	26,4	2,8
Ethyl styrene	1)	7,1	1,9
Decene	1)	1)	1)
Methyl indene	1)	19,6	2,7
Naphthalene	6	205	103
Methyl naphthalene			1)

1) Present but concentration too low to measure.

Summary of chemical groups

Proportion	Fire: Wood			Polypropylene		
	Growth	Steady State	Decay	Growth	Steady State	Decay
Total	54	2 584	429	1 129	4 526	2 080
% Oxygenated organics	36	30	35	11	5	3
% Unsaturated hydrocarbons	27	20	19	72	47	44
% Saturated hydrocarbons	22	4	2	1	22	17
% Aromatic hydrocarbons	15	46	44	16	26	36
% Organics to carbon monoxide	5	6,5	7,1	376	57	14

Table 2 — General classification of fires

Fire	Oxygen[1] %	Ratio CO_2/CO[2]	Temperature[1] °C	Irradiance[3] kW/m^2
1 Decomposition				
a) Smouldering (self-sustained)	21	N/A	< 100	N/A
b) Non-flaming (oxidative)	5 to 21	N/A	< 500	< 25
c) Non-flaming (pyrolytic)	< 5	N/A	< 1 000	N/A
2 Developing fire (flaming)	10 to 15	100 to 200	400 to 600	20 to 40
3 Fully developed (flaming)				
a) Relatively low ventilation	1 to 5	< 10	600 to 900	40 to 70
b) Relatively high ventilation	5 to 10	< 100	600 to 1 200	50 to 150

1) General environmental condition (average) within compartment.

2) Mean value in fire plume near to fire.

3) Incident irradiance on to sample (average).

Table 3 — Summary of principal laboratory methods

Method	Combustion device	Furnace temperature	Air flow	Quantity of material	Animals/No. per test	Exposure mode	Exposure duration	Toxicity measurements[6]	Chemical analyses
DIN	Movable annular tube furnace	Fixed, 200 °C to 600 °C	Dynamic	Fixed, same volume or weight	Rats, at least 5, usually 20	Head-only or whole body	30 min	LC_{50} (30 min + 14 day) and others	CO, CO_2, O_2, selected gases COHb
CAMI	Tube furnace	Fixed, 625 °C	Static, recircu-lating	Fixed, 0,75 g[1]	Rats, 3, at least 3 tests	Whole body	30 min	t_i and t_d[1]	CO, CO_2, O_2, HCN, selected gases
NBS	Crucible furnace	Fixed, 25 °C below auto-ignition temperature	Static	Varied, 8 g maximum	Rats, 6	Head-only	30 min[2]	LC_{50} (30 min + 14 day)	CO, CO_2, O_2, COHb
US-Rad	Radiant furnace	Fixed, heat fluxes up 5 W/cm^2	Static	Surface area varied	Rats, 6	Head-only	30 min	LC_t, values defining major categories of toxic potency	CO, CO_2, O_2
U-PITT	Tube furnace	Programmed to 600 °C above 0,2 % weight loss temperature	Dynamic	Varied	Mice, 4	Head-only	30 min from 0,2 % weight loss[3]	RD_{50}[7], LC_{50}, (30 min + 10 min), S1, asphyxiation range, histo-pathology, IT_{50}	CO, CO_2, O_2 HCN selected gases
USF	Tube furnace	Fixed or programmed 200 °C to 800 °C	Static or dynamic	Normally fixed, 1 g varied to obtain LC_{50}	Mice, 4, at least 2 tests	Whole body	30 min	t_i and t_d[4]	CO, CO_2, O_2 selected gases
JGBR[5]	Radiant heat furnace	Programmed to 600 °C from room temperature	Dynamic	Surface area fixed at 324 cm^2	Mice, 8	Whole body	15 min	t_i	CO, CO_2, O_2, HCN, HCl selected gases

1) CAMI method modified for fixed or programmed heating, flaming or non-flaming combustion and determination of LC_{50}.

2) Optional 10-minute exposure to 30 mg/l of $IC_{50} \geqslant 2$ mg/l to determine if material rapidly produces toxic products.

3) Except for determination of sensory irritation.

4) PSC modified USF method to vary quantity of material and measure LC_{50} and LT_{50}.

5) Significant modifications are under development particularly on the combustion system.

6) The term LC_{50} implies an acute toxicity evaluation including determining the nature of the toxicity and estimating the LC_{50} as an index of toxic potency.

7) RD = Respiratory depression.

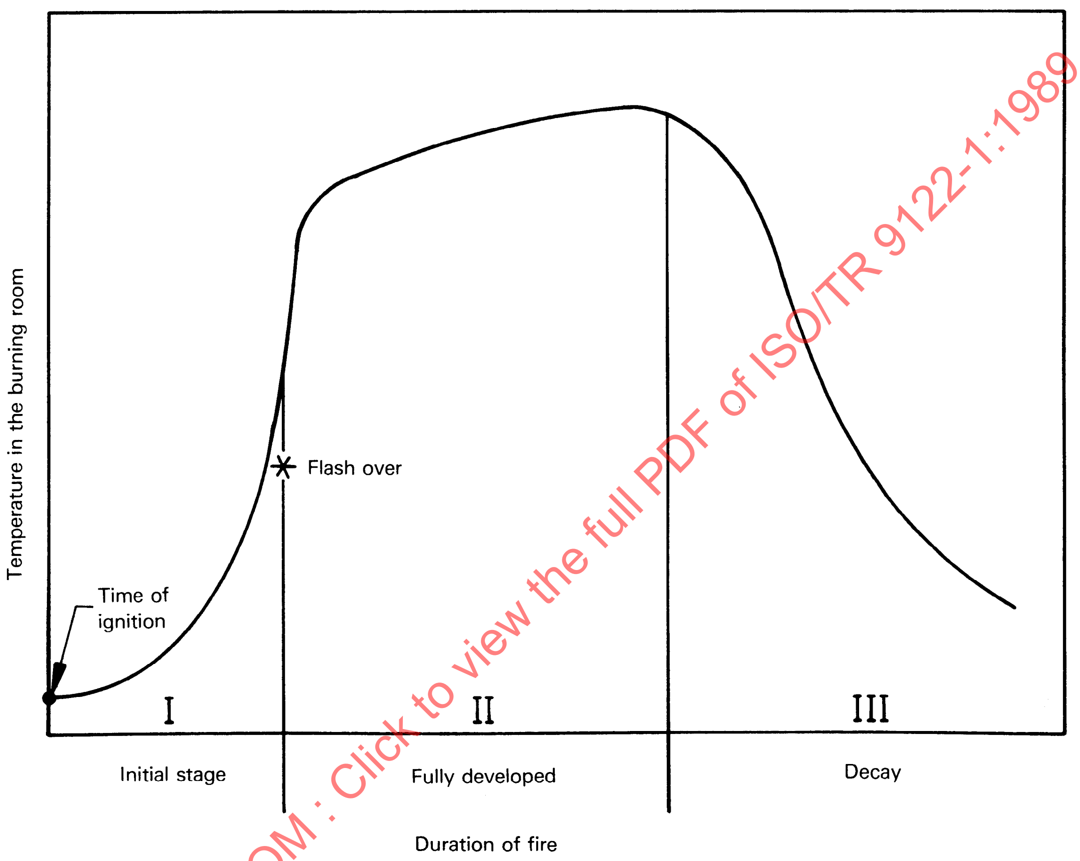

Figure 1 — General temperature-time curve of fire development in rooms