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Toxic Gases and Vapours Produced at Fires

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Please note

Toxic gases and vapours produced at fires are responsible for a large number of fire deaths. If those resulting from clothing fires are excluded, more victims are claimed by the products of fire than by burns. Fire statistics reveal that of the total number of deaths at building fires, again omitting those due to ignition of clothing, approximately 50 per cent are due to combustion products. This figure should probably be even higher since it is difficult to be certain whether death has resulted from burns or toxic combustion products when victims are severely burned.

Smoke and toxic gases and vapours usually occur together at fires and it is difficult to distinguish clearly which product of combustion is responsible for the harmful effects. Before discussing them, smoke, gas and vapour should be defined as these terms are used in the present Digest. Smoke is particulate matter consisting of very fine solid particles and condensed vapour. It constitutes most of the visible part of the products of combustion observed at a fire. Gas is a product of combustion that remains a gas even when cooled to normal building temperatures. Vapour is a product of combustion that is gas when produced but reverts to solid or liquid at normal temperatures. Vapours will gradually condense on cool surfaces as they migrate from the fire.

The main danger from smoke is reduced visibility; that from toxic gases and vapours, their adverse effect on body functions. Smoke will often impede the escape of occupants from a burning building and result in prolonged exposure to the harmful effects of toxic products. Toxic gases and vapours can cause death if they are present in sufficient quantities and for a sufficient time. Certain ones can also trap occupants by acting as irritants. For example, small concentrations of products such as hydrogen chloride and ammonia cause direct irritation of the respiratory tract and the eyes. Although irritants may serve as warning agents and alert occupants to fire, under certain circumstances they can prevent victims from finding an exit even before reduced visibility from smoke traps them.

Fire authorities have long been concerned with the life hazard associated with toxic combustion products. Its seriousness for fire fighters was recognized by the fire service many years ago and almost all modern fire departments are now equipped with self-breathing apparatus. The danger to occupants of buildings is also recognized, but so far it has appeared impractical to limit the use of combustible materials, until recently essentially cellulose, either as building materials or as goods and furnishings. Of recent years various new materials, especially synthetic polymers, have found increasing use in buildings and their introduction has heightened the concern of fire authorities with reference to toxic combustion products. Part of this increased concern has arisen because of the lack of information on the toxic combustion products produced.

The authors of this Digest are not aware of any regulations in Canada limiting use of materials that generate large amounts of toxic combustion products. Regulations based on this characteristic were, until recently, uncommon in other countries also, but they are now being introduced in building codes in the United States. For example, as one of the requirements for interior finish and trim of buildings, the BOCA Basic Building Code 1970 [(1)] specifies: "interior finish materials that give off smoke or gases more dense or more toxic than that given off by untreated wood or untreated paper under comparable exposure to heat or flame shall not be permitted."

Physiological Response to Various Toxic Products

The toxic products responsible for fire deaths are usually not known because detailed pathological examination of fire victims is rarely conducted. Some information on the pathological response of man to various harmful gases and vapours produced at fires is available, however [(2,3,4)].

Carbon Monoxide

Carbon monoxide (CO) is produced as a result of incomplete combustion of materials containing carbon and is present in large quantities at most fires. Carbon monoxide that is inhaled causes asphyxiation by combining with haemoglobin in a reversible reaction to form carboxyhaemoglobin. Its formation at the expense of oxyhaemoglobin reduces the availability of oxygen for the cellular systems of the body. Anoxaemia induced by carbon monoxide does not, as with simple asphyxiants, cease as soon as fresh air is inhaled. After even moderate degrees of gassing, only about 50 per cent of the carbon monoxide is eliminated in the first hour under ordinary circumstances; complete elimination under the action of fresh air is not effected for many hours. The highest concentration of CO to which man may be exposed day after day without adverse effect is 50 ppm (Table I). Above this level, symptoms such as headache, fatigue and dizziness appear in healthy individuals.

Table I. Physiological Response to Various Concentrations of CO

	Parts of CP per million parts of air
Threshold limit value	50
concentration which can be inhaled for 1 hour without appreciable effect	400 to 500
Concentration causing unpleasant symptoms after 1 hour of exposure	1000 to 2000
Dangerous concentration for exposure of 1 hour	1500 to 2000
Concentrations that are fatal in	4000 and

exposure of less than 1 hour	above

Carbon Dioxide

Carbon dioxide (CO_2) is produced in quantity at most building fires. Inhalation of carbon dioxide stimulates respiration and this in turn increases inhalation of both oxygen and possible toxic gases and vapours produced by the fire. Stimulation is pronounced at 5 per cent (50,000 ppm) concentration, and 30-minute exposure produces signs of intoxication; above 70,000 ppm unconsciousness results in a few minutes. The threshold limit for CO_2, that is the concentration that can be tolerated by workers day after day without adverse effect, is 5,000 ppm.

Hydrogen Cyanide

Hydrogen cyanide (HCN) is produced when materials that contain nitrogen in their structure, e.g., orlon, nylon, wool, polyurethane, urea-formaldehyde and ABS (acrylonitrile-butadiene-styrene) are involved in fire. Hydrogen cyanide and other cyanogen compounds arrest the activity of all forms of living matter. They exert an inhibiting action on the use of oxygen by the living cells of the body tissues. The physiological response to various concentrations of hydrogen cyanide is presented in Table II.

Table II. Physiological Response to Various Concentrations of Hydrogen Cyanide

	Parts of HCN per million parts of air
Threshold limit value.	10
Slight symptoms after several hours of exposure.	20 to 40
Maximum amount that can be inhaled for 1 hour without serious disturbance.	50 to 60
Dangerous in 30 minutes to 1 hour.	120 to 150
Rapidly fatal.	3000

Hydrogen Chloride

Hydrogen chloride (HCl) is produced when polyvinyl chloride (PVC) is decomposed at fires. If inhaled, HCl will damage the upper respiratory tract and lead to asphyxiation or death. The physiological response of man to various concentrations of HCl is given in Table III.

Table III. Physiological Response to various Concentration of HC1

	Parts of HC1 per million parts of air
Threshold limit value	5
Maximum concentration allowable for short exposure (½ to 1 hour).	50
Dangerous for even short	1000 to 2000

exposure.

Nitrogen Dioxide

There are three common oxides of nitrogen: nitrous oxide (N_2O), nitric oxide (NO), and the two forms of the dioxide (NO_2 and N_2O_4). Nitrogen dioxide, which is very toxic, can be produced from the combustion of cellulose nitrate. Nitric oxide does not exist in atmospheric air because it is converted into dioxide in the presence of oxygen. These compounds are strong irritants, particularly to mucous membranes and thus when inhaled will damage tissues in the respiratory tract by reacting with moisture to produce nitrous and nitric acids.

The physiological response of man to various concentrations of nitrogen dioxide is given in Table IV.

Table IV. Physiological Response to Various Concentrations of Nitrogen Dioxide

	Parts of NO_2 per million parts of air
limit value.	5
mount causing e irritation to the	62
s for even short	117 to 154
fatal for short	240 to 775

Formation of Toxic Gases and Vapours

The quantities of toxic gases and vapours produced by combustion depend on the material involved and the environmental condition. Some are already known; others can often be predicted from a knowledge of the chemical composition and molecular structure of organic compounds. A basis for prediction is important, both to research work in identifying combustion products and to designers. Fire and building officials could also benefit from a knowledge of the chemical composition of materials because chemical composition dictates which toxic products will be produced from the combustion of a given material. The following examples will illustrate how formation of the main toxic combustion products may be predicted from a knowledge of chemical composition of materials.

Polyethylene

Polyethylene is a polymer consisting of carbon and hydrogen atoms. When this material is burned under ideal conditions with a hot fire and ample supply of oxygen, the main products are carbon dioxide and water. Under adverse conditions, for example when the oxygen supply is limited, carbon particles and carbon monoxide, which is toxic, will also be formed. Carbon monoxide is the main toxic gas produced from the combustion of polyethylene and other organic materials that are made up of carbon and hydrogen atoms.

Polystyrene

Polystyrene also is made of carbon and hydrogen atoms. When this polymer is decomposed by heat, the major product is styrene, the compound from which it was produced. In a fire, styrene is broken down further to smaller molecules that react with oxygen to form the usual combustion products. The main toxic product from the burning of polystyrene is also CO. The product, styrene, is almost as toxic as CO, but it is produced in much smaller quantities [5].

Polyvinyl Chloride (PVC)

PVC is made of carbon, hydrogen and chlorine atoms. When this polymer is decomposed by heat the chlorine atoms are broken off and each combines with a hydrogen atom to form hydrogen chloride (HCl), which is not only toxic but also very corrosive. Phosgene ($COCl_2$), which is very toxic, is produced in negligible amounts from the combustion of PVC. Hydrogen chloride is more toxic than CO and may be produced in greater quantity than CO when PVC is involved in a fire.

Polymethylmethacrylate (plexiglas or perspex)

When plexiglas is heated, the major decomposition product is methylmethacrylate, the compound from which it was synthesized. In a fire, methylmethacrylate is broken down to smaller molecules that react with oxygen to form the usual combustion products. The main toxic combustion product of plexiglas is CO. The toxicity of methylmethacrylate is of the same order as that of CO, but it is produced in much smaller quantities.

Wood and Cellulose

Cellulose, the main constituent of wood, is made of carbon, hydrogen and oxygen atoms. The burning of cellulose produces hydrocarbons and compounds made of these three elements, in addition to the usual combustion products. Some of the oxygen-containing vapours, especially the aldehydes, are very toxic. It is generally accepted, however, that CO is responsible for most deaths at fires involving cellulose materials because it is produced in much greater quantities than other toxic gases.

Acrylic Fibres (polyacrylonitrile)

Several important synthetic fibres have a high acrylonitrile content of 80 to 85 per cent. These synthetic materials are made of carbon, hydrogen and nitrogen atoms, and when they are decomposed in a fire they produce hydrogen cyanide (HCN), a very toxic gas, plus CO and other combustion products.

Hydrogen cyanide also is produced from the combustion of ABS (acrylonitrile-butadiene-styrene) pipe and acrylic carpeting materials, which are synthesized using acrylonitrile. It is also produced by the combustion of other compounds that contain nitrogen in their structure such as urea-formaldehyde, nylon, wool and polyurethane.

Evaluation of Toxic Combustion Products

Many investigators have undertaken studies on toxic combustion products of organic materials with the object of making a realistic assessment of hazard. One method of evaluating the toxic gas-producing potential of materials is by burning a material in an enclosure and subjecting animals to the resulting atmosphere. Work has also been conducted in which toxic combustion products are identified and quantitatively analysed. The relatively small progress that has been made over the years indicates the complexity of the problem. Some progress has recently been made, however, largely owing to advances in analytical techniques such as gas chromatography and mass spectrometry.

Summary

Toxic gases and vapours produced by combustion are responsible for the majority of deaths at building fires. For this reason fire authorities would like to consider regulations to restrict use of materials that produce large amounts of smoke and toxic gases. At present, there are very few regulations limiting the use of materials based on this property, but it is conceivable that more regulations will be adopted in the future.

Information on toxic gases and vapours produced by combustion of materials commonly found in buildings is still very limited. Some quantitative data on the toxic compounds mentioned in this Digest are now available, but data on many other toxic combustion products produced in small quantities are very scarce. Knowledge is also lacking of differences in burning rates (and resulting rates of production of toxic gases) of materials under comparable conditions of burning and differences in rates of condensation of products as they migrate away from the fire.

Carbon monoxide is produced in quantity at most building fires because most organic materials contain carbon in their chemical structure. Materials that contain nitrogen, such as acrylic fibre, nylon, wool and urea-formaldehyde foam, could produce dangerous quantities of HCN in addition to CO. When these materials are involved in fire, the resulting atmosphere could be more toxic than that from the combustion of an equal amount of material whose toxic product is mainly CO. Materials that contain a large proportion of chlorine, such as PVC, could also be very harmful at fires. They would produce HCl in addition to CO.

The present state of knowledge of toxic combustion products is probably not sufficient to guide the designer in his choice of combustible materials to be used in buildings. This Digest was prepared to keep him abreast of the problem and the efforts that are being made in this field.

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