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Toxicity testing of fire effluents -- Part 5: Prediction of toxic effects of fire effluents

Essais de toxicité des effluents du feu -- Partie 5: Prédictions concernant les effets toxiques des effluents du feu

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Toxicity testing of fire effluents —

Part 5:
Prediction of toxic effects of fire effluents

Essais de toxicité des effluents du feu —

Partie 5: Prédictions concernant les effets toxiques des effluents du feu

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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. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

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

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

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

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 Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 9122-5, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92, *Fire tests on building materials, components and structures*, Sub-Committee SC 3, *Toxic hazards in fire*.

This document is being issued in the type 2 Technical Report series of publications (according to subclause G.4.2.2 of part 1 of the IEC/ISO Directives) as a "prospective standard for provisional application" in the field of toxicity testing of fire effluents because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this type 2 Technical Report will be carried out not later than two years after its publication with the options of: extension for another two years; conversion into an International Standard; or withdrawal.

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

— *Part 1: General*

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

— *Part 3: Methods for the analysis of gases and vapours in fire effluents*

— *Part 4: The fire model (furnaces and combustion apparatus used in small-scale testing)*

— *Part 5: Prediction of toxic effects of fire effluents*

Annexes A and B of this part of ISO/TR 9122 are for information only.

Toxicity testing of fire effluents —

Part 5:
Prediction of toxic effects of fire effluents

1 Scope

This part of ISO/TR 9122 reviews the progress of bioanalytical methodology, including the application of mathematical models which are available and may be used in the toxicological assessment of fire effluent atmospheres. Attention is also given to the application of such models as a means to minimize the use of laboratory animals in the testing of materials for fire effluent toxicity.

2 Background

A major thrust in the assessment of the toxic effects of fire effluents has been in the development of mathematical models for predicting such effects from appropriate data on the composition and concentrations of the fire gases. The objectives of these efforts are twofold. Assessment of smoke toxicity from analytical data could obviate much of the use of live animals in conventional bioassay methodology. Furthermore, providing that both qualitative and quantitative differences in toxicological effects between laboratory animals and man are understood, such modelling methodology can also be used for estimating the time to development of untenable conditions in either real or simulated fire scenarios.

The development of smoke toxicity modelling began in the late 1960's and continued into the 1970's, with concepts proposed by Y. Tsuchiya and K. Sumi at the National Research Council Laboratories in Canada[1 and 2]. A deterrent to its acceptability at that time was the widely-held perception that the toxicity of smoke could be as complex and as exotic as its composition. However, work in the United Kingdom by D.A. Purser and W.D. Woolley[3] demonstrated that smoke toxicity could, to a large extent, be explained both qualitatively and quantitatively in terms of a small number of important toxic gases. This provided support for the potential validity of smoke toxicity modelling. A publication in 1981 by S.C. Packham and G.E. Hartzell[4] together with the work of P.W. Smith[5], established a foundation for such modelling in the United States. Research in this area advanced considerably during the 1980's, such that more recent publications by G.E. Hartzell[6 to 8], B.C. Levin[9 and 10], D.A. Purser[11] and Y. Tsuchiya[12] set the stage for the development of toxic hazard modelling which takes into account combinations of toxic insults as they would occur in a fire.

3 General concepts

Basic to all the modelling techniques is some expression of the concentration of a toxicant relative to that concentration known to cause a particular toxic effect resulting from a given time of exposure. Lacking in some of the early development efforts was a clear concept of the "dose" of a toxicant, along with appreciation of its utility as a tool in modelling. Also lacking was a good base of toxicological data appropriate for short exposures to relatively high concentrations of toxicants. Additionally, there was insufficient understanding of relevant laboratory decomposition models upon which the toxicological modelling was to be based.

Quantification of "dose" has been fundamental to the development of methodology for modelling the toxicological effects of inhalation of fire gases, whether in laboratory animals or humans. Physiological responses are usually dose-related, i.e., the magnitude of the effect increases with increasing amounts or accumulated body burden of a physiologically active agent. Since the actual dose of toxicants from inhalation of fire effluents cannot be measured directly, the assumption is made that the dose is a function of fire effluent (or toxicant) concentration and exposure time[13]. This dose is really an expression of the insult to which a subject is ex-

posed. The term "exposure dose" is probably more accurate and has become the preferred term in combustion toxicology.

Concentrations of common fire gas toxicants, such as carbon monoxide and hydrogen cyanide, are usually expressed as parts per million by volume [ppm (*V*/*V*)]. Therefore, the exposure dose can be expressed as the product of the concentration, C, and time, t, (usually expressed in ppm·min). In the case of a changing concentration of a gaseous toxicant, the exposure dose is actually the integrated area under a concentration vs. time curve.

Often, the concentrations of fire gas toxicants are not known. In that event, one can still deal with the concept of exposure dose as it applies to smoke. Since smoke concentration cannot be quantified, an approximation is made that the smoke concentration is proportional to the mass loss during a fire. The integrated area under a mass loss per unit volume vs. time curve thus becomes a measure of smoke exposure dose (usually expressed in $g \cdot m^{-3} \cdot min$)[14 and 15]. (This concept of smoke exposure dose is described in ISO/TR 9122-2.) Smoke exposure dose at any point in time can be calculated from data obtained from a laboratory combustion device, instrumented experimental fires, data generated from mathematically modelled fires and even data estimated from real fires.

In order to model the toxic effects of exposure to fire effluents, it is necessary to obtain two basic pieces of information:

a) the exposure dose $C \cdot t$ generated by the fire (for the major toxic gases in the smoke or for the mass loss of the materials being combusted); and

b) the exposure dose $C \cdot t$ required for a given toxic effect (lethality or incapacitation).

Elementary approaches to estimation of toxic hazards can be based on simple mass loss per unit volume data, i.e. how much fire load is consumed and into what volume it has been dispersed. Recognizing that most materials typically exhibit 30 min LC_{50} values for their fire effluents in the range of approximately 30 $g \cdot m^{-3} \cdot min$[16], the US National Institute of Standards and Technology Hazard I Model uses a lethal tenability limit of 900 $g \cdot m^{-3} \cdot min$[17] if actual material data is unavailable. The British Standards Institution, somewhat more conservatively, employs a value of 500 $g \cdot m^{-3} \cdot min$[18]. These simple methods avoid the use of individual material LC_{50} values, which are not always known.

In the case of real fire scenarios, smoke transport, dilution and layering calculations can provide for estimation of smoke exposure doses presented at the breathing zone of subjects even in areas remote from a fire[17]. It is an important concept that "toxicological exposure doses" can be visualized as quantified entities that are generated from a fire, transported and then administered to exposed subjects.

4 Predictions involving one single fire gas

The simplest form of modelling involves the situation in which only one toxic fire gas is considered and where exposure doses associated with given effects, e.g. incapacitation or death, are constants for any exposure concentration (i.e. Haber's rule is valid and $C \cdot t = k$, where k is a constant exposure dose required for a given toxic effect). Unfortunately, this may not be the case over the range of concentrations of interest and it is desirable to determine the dependence of the effective exposure dose on the concentration of the toxicant. In practice it has been found that the exposure dose required to cause a particular response decreases with increasing concentration of a toxicant.

Numerous laboratory studies have involved the most prevalent gaseous fire effluents, i.e. CO, CO_2, O_2, HCN, HCl, HF and NO_2, with exposure doses associated with lethality of rodents (mice, rats and guinea pigs) being reasonably well characterized. LC_{50} values from the literature are given in tables A.1 to A.6. With the inclusion of some limited data on macaque monkeys, baboons and humans, the data appear to suggest that, overall, the rat may be a reasonable model for humans with regard to lethality. (Sublethal effects, especially respiratory effects of irritants, are another matter, and the rat may not be an adequate model; however, some data are available for primates and humans.)

Once effective exposure doses are characterized, the concepts of the fractional exposure dose, along with the summation or integration of fractional exposure doses, result in workable tools in combustion toxicology[5 to 9, 11, 17 and 19]. Incremental exposure doses $C \cdot dt$ are calculated and related to the specific $C \cdot t$ exposure dose required to produce the given toxicological effect. Thus a fractional effective dose (FED) is calculated for each small time interval. Continuous summation of these fractional effective doses is carried out in order to calculate the accumulated exposure dose.

Mathematically, the model for an individual toxicant i can be expressed as:

$$\int_{t_0}^{t} \frac{C_i}{(C \cdot t)_i} \, dt \qquad \ldots (1)$$

Most toxicological modelling methodologies make use of this concept in one form or another.

5 Predictions involving multiple fire gases

There are two methods for predicting the toxic effects of fire effluent atmospheres containing multiple

toxicants. One is an empirical method involving mass loss measurements combined with toxic potency data of the material involved obtained from animal exposure data; the other is based upon analysis of the composition of the atmosphere in terms of the major known toxic products. The latter is then used to make predictions from the known effects of these gases and the interactions between them.

5.1 Use of mass loss measurements

This approach may be used to make assessments of the toxic effects, in particular lethality, of mathematically modelled fires, large scale experimental fires or real fire scenarios involving one or more materials.

For this method, it is necessary to determine the rate of mass loss of the materials in the fire, either by direct measurement or by mathematical modelling of fire growth and mass loss. The latter is based upon input data from small scale tests or other sources. The mass loss curve for the fire is then used in conjunction with toxic potency data for the specific materials as derived from small scale bioassay tests. The basic method for the determination of the toxic potency of the combustion products from individual materials is to perform a small scale combustion toxicity test on a material under conditions relevant to those in the fire and to find the lethal mass loss exposure dose (LCt_{50}) expressed in $g \cdot m^{-3} \cdot min$ or the equivalent. The mass loss curve for each material in the full scale fire is used to perform a fractional effective dose (FED) analysis in the same way as for a single gas as described previously. Where several materials are involved in a fire, the FEDs of each material are summed since, in practice, each material produces certain yields of the common major toxicants which are mixed together in the smoke. A number of practical and essentially similar methods for applying this approach have been published [8, 11, 17 and 18].

The advantage of this approach is its simplicity, since it requires a knowledge only of the mass loss concentration curve for the materials involved in the fire and the toxicities of those materials in terms of mass loss $C \cdot t$ products. It is robust in that, in practice, LCt_{50}s of many tested materials have been shown from small scale tests to fall into approximately one order of magnitude[11 and 16].

The disadvantages are that it normally only provides lethality information and does not allow for physiological deviations from ideal behaviour. It is also necessary to assume that lethal exposure doses in rats are similar to those in humans. Further, the method assumes that the toxicity of a material in a real fire will be the same as that in a small scale test. The last objection is probably the most serious limitation, but it can be overcome to some extent providing that care is taken that the small scale bioassay combustion toxicity tests on materials are conducted under conditions similar to those in the full scale fire. Thus, where toxic effects are being assessed for a fire that starts in the non-flaming mode and progresses through early flaming to become a large post-flashover fire, it will be necessary to use different lethal mass loss exposure doses for each stage of the fire.

5.2 Use of analyzed concentrations of major toxicants

This approach makes predictions of toxic effects based upon chemical analysis of the primary combustion products in the fire effluent along with knowledge of the toxic effects and toxic interactions of these products. It has two types of application. One is to replace or limit the use of animals in small scale bioassay combustion toxicity tests. If the lethal exposure dose to rodents for a particular test atmosphere from a material can be predicted from the measured atmosphere composition, then animal exposures can be avoided or used in a limited way to confirm the prediction. The other application is to make predictions of the likely incapacitating or lethal effects of exposure of humans to large scale or real fire atmospheres. This assumes a correlation between animal and human responses.

The full consequences of exposure to atmospheres containing multiple toxicants have only recently been examined in detail. Toxic fire gases may be classified into two main types, those whose main effect is to cause tissue hypoxia by impeding the delivery or use of oxygen in the tissues (carbon monoxide, hydrogen cyanide and low oxygen hypoxia) and those that are irritant, causing pain and tissue damage upon contact with the eyes and respiratory tract epithelium (principally organic irritants and acid gases). In addition to these, carbon dioxide is important, particularly due to its effects on respiration. A final class may be assigned as "unusual" toxicants.

Since the main fire gases within each class exert similar physiological effects through related mechanisms, it is not surprising that they are basically additive in their overall effects. What is now emerging is that, although these main classes of gases exert rather different physiological effects through different mechanisms, when all are present in mixtures, each can result in a certain degree of compromise experienced by an exposed subject and these effects are roughly additive in contributing to incapacitation or death. It should not be unexpected that varying degrees of a partially compromised condition may be roughly additive, since an examination of the physiological mechanisms whereby these toxicants exert their effects reveals a number of possible interactions, and these effects have been demonstrated in a number of studies. This principle of additivity is a key element in the assessment of toxicity from analytical data.

One of the reasons for these interactions, and a further complication with combined toxicants which is

more difficult to deal with, is that an individual toxicant may have physiological effects other than those of its principal specific toxicity. One obvious and very important effect is when toxicants affect respiration. Hydrogen cyanide causes hyperventilation, with up to four-fold increases in ventilation (respiratory minute volume RMV) being reported for monkeys early in an exposure[20]. This hyperventilation in primates (which eventually slows as narcosis results) can result in faster incapacitation from HCN itself than would otherwise be expected, along with more rapid uptake of CO and formation of carboxyhaemoglobin (COHb), should CO also be present. Similarly, carbon dioxide, although relatively innocuous itself at concentrations of up to 5 %, is a powerful respiratory stimulant causing an approximate doubling of respiration at a concentration of 3 % to 4 % and trebling of respiration at 5 % to 6 %[11]. This increases the rate of uptake of any other toxicants present approximately in proportion to the increase in ventilation. The inhalation of irritants also affects respiration and thereby can affect the uptake of asphyxiant gases. Although in the rat, respiratory depression resulting from HCl inhalation can slow the uptake of CO[21], inhalation of irritants such as HCl by primates tends to cause an increase in RMV[3]. Lung function changes are induced which appear to impair oxygen uptake into the blood[22], thereby potentially adding to the hypoxic effect of inhaled narcotic gases.

Allied to these respiratory effects is the development of acidosis. Evidence is emerging that metabolic acidosis, resulting from tissue hypoxia induced by gases such as CO and HCN, combined with respiratory acidosis caused by inhalation of CO_2, or stagnant hypoxia induced by irritants, can result in toxic effects not obviously predictable from the effects of the individual gases[9, 23 and 24]. With all these effects possible in the inhalation of mixtures of toxicants in real fire effluents, the situation is extremely complex. Very little research using toxicant combinations has been conducted using primates and the full extent of the combined effects on incapacitation and death of humans exposed to fire gas combinations is not yet fully understood.

In spite of the complexity of dealing with atmospheres containing multiple toxicants, considerable progress has been made in confirming and quantifying some of these effects from studies with rodents. For example, it is now well established that carbon monoxide and hydrogen cyanide are additive when expressed as fractional exposure doses required to cause a toxic effect[7, 9 and 10]. This effect has also been reported for dogs and primates[25 and 26]. Thus to a reasonable approximation, the fraction of an effective exposure dose of CO can be added to that of HCN in estimating the presence of a hazardous condition. When low oxygen is added to either or both of these hypoxic gases, there is evidence that a further additive effect occurs based on studies in rodents[9, 27 and 28] and humans[29]. The effect of CO_2 in increasing the rate of uptake of other toxic gases has already been mentioned, but apart from this, it is a narcotic in its own right at concentrations above 5 %, causing impairment or loss of consciousness in humans. Increased incidence of lethality (particularly postexposure), has been observed with certain combinations of CO and CO_2[23], possibly associated with the combined insults of respiratory acidosis (from the CO_2) with metabolic acidosis (caused by the CO), a condition from which the rodent has difficulty recovering postexposure. Other studies with rats involving CO_2 have shown combinations of CO_2 and NO_2 to exhibit synergism[24].

In the case of mixtures of hypoxic gases and an irritant gas (hydrogen chloride), analysis of the toxicological data shows that exposure doses leading to lethality of rats can also be additive[21 and 30]. Although not yet confirmed with primates, these studies imply that hydrogen chloride can be much more dangerous than previously thought when in the presence of carbon monoxide (and vice versa). A rapid respiratory acidosis was seen in the blood of rats exposed to HCl which, when coupled with the metabolic acidosis produced by the CO, resulted in severely compromised animals. It is also possible that in humans impairment of oxygen uptake into the blood occurs as a result of ventilation perfusion changes caused by inhalation of irritants. This can also be additive with the hypoxic effects of CO and other gases. These effects can have significance with regard to human fire exposures, impairing escape capability and leading to a prolonged hypoxaemia following rescue. The importance of these phenomena to humans is supported by evidence that the incapacitating effects of carbon monoxide can be enhanced in primates upon simultaneous exposure to HCl, the presence of which causes the partial pressure of oxygen in the arterial blood to be decreased[22]. This is presumably the case with other irritants as well. It has been observed that there can also be additivity of fractional effective doses between HCl and HCN[30]. Particularly striking was the incidence of postexposure deaths from concentrations of the toxicants, each of which alone would not be expected to result in any postexposure lethality. Deaths often occurred several days after exposure.

Interactions between multiple combinations of fire effluent toxicants have been particularly well studied using mice, by T. Sakurai at the Research Institute of Marine Engineering, Higashimurayama, Japan[27]. In general, these studies confirmed the effects reported and predicted by other investigators, giving additional confidence to predictive modelling by the methodology described.

A current limitation on the predictive power of gas combination toxicity models is in the area of irritancy. Only a small number of irritant chemicals are routinely measured in smoke, although at least twenty have been identified. There is also evidence that smoke is more irritating in practice than would be predicted

from even a comprehensive analysis of its composition, so that other factors, in addition to simple chemical toxicity, are possibly involved[11]. Two that have been identified as important are the irritant effects of particulate matter (soot) carrying adsorbed toxicants deep into the lung and the possible role of free radicals in smoke in causing deep lung damage[11]. These areas require further investigation in order to improve the predictive power of models. Currently, the only way that smoke irritancy can be factored into models is to use data on irritancy from small scale bioassay tests. It is to be hoped that following further research on the toxicity of important irritants, as well as improved chemical analysis of combustion product atmospheres, it will be possible to predict these effects as effectively as those of hypoxic gases can now be predicted.

6 Fractional effective dose models

6.1 Mass loss models

The development of toxic conditions and estimates of toxic hazard in full scale fire scenarios can be made from mass loss (mass burned) concentration-time profiles and toxic potency data for the materials involved. The justification for this approach is based upon the demonstrated additivity of fractional effective doses (FEDs) of many of the individual toxic gases in fires.

6.1.1 Hartzell-Emmons mass loss FED model

Using this concept, an FED model using mass loss toxicity data for individual materials has been developed[8]. The FED model takes the form of expression (2) for n materials. The total fractional effective exposure dose at any time, t, would be:

$$\sum_{i=1}^{n} \int_{t(b_i)}^{t} \frac{C_i - b_i}{K_i} \, dt \qquad \ldots (2)$$

where

C_i represents smoke concentration (from mass burning rate data);

K_i and b_i characterize the toxicity of component i. The values for K_i and b_i are respectively the slope and intercept of a plot of LC_{50} vs. 1/time-of-exposure for component i.

In order to prevent "negative doses" from accumulating when C_i is less than b_i, the lower limit for the integration is the value of t_i when C_i is equal to b_i. The time at which expression (2) becomes unity (100 %) is the time of exposure which would be expected to result in 50 % effect. Computer programs, using a variety of fire scenarios and material input data, have been developed for assessing potential toxic hazard for fires involving several materials simultaneously.

6.1.2 Purser mass loss FED model

A similar model has been proposed by Purser which also relies upon knowledge of mass loss burning rate and dispersal volume[11]. A simple, elementary calculation makes use of a single average mass loss exposure dose for lethality for all materials of 300 $g \cdot m^{-3} \cdot min$. For more advanced calculations, use is made of LCt_{50} data for individual materials obtained under conditions relevant to the fire condition being modelled (non-flaming, early flaming or post-flashover).

6.1.3 British Standards Institution mass loss FED model

A third, and quite similar model has been published by the British Standards Institution[18]. This model also relies on knowledge of the mass loss burning rate for each material in the fire and the volume into which the products are dispersed. Individual materials are allocated toxic potency factors relative to wood (derived from small scale LCt_{50} data) for input into the calculation.

6.1.4 National Institute of Standards and Technology (USA) Hazard I model

The tenability (TENAB) routine used in the Hazard I computer program allows the utilization of a mass loss rate model, with input supplied by the Fire and Smoke Transport (FAST) part of the model[17]. FAST is a program which calculates the evolving distribution of smoke and fire gases and the temperature throughout a building during a fire. FAST essentially solves a set of equations that predict the change in the energy (and thus temperature) and mass (and thus the smoke and gas concentrations) over small increments of time. The changing exposure of an occupant moving through the building or overtaken by the descending layer are accounted for by adding (integrating) these concentrations over time in TENAB. For example, an occupant is initially exposed to the lower layer until the interface reaches head height. The time that this occurs is obtained from the interface position data for that room. Thus, the exposure at any time equals the accumulated $C \cdot t$ value up to that time. When moving from room to room, the accumulated exposure dose for each room is computed. The total exposure is the sum of the exposure doses accumulated in each room until the occupant exits the building. In the absence of other information, all materials, are assumed to have LCt_{50} values of 900 $g \cdot m^{-3} \cdot min$. Other values can be chosen by the program operator in order to address incapacitation, for example.

6.2 Toxic gas models

These methods all depend upon knowledge of the composition of a combustion product atmosphere as a function of time during a fire or fire test, and of the