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Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires

Composants dangereux du feu — Lignes directrices pour l'estimation du temps disponible avant que les conditions de tenabilité ne soient compromises

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Foreword

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ISO 13571 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 3, *Fire threat to people and environment*.

This second edition cancels and replaces the first edition (ISO 13571:2007), which has been technically revised.

Introduction

Estimation of occupants' tenability when exposed to a fire environment ultimately involves their ability to perform cognitive and motor-skill functions at an acceptable level. Generally, acceptable performance may include any of a number of desirable outcomes, including escape to a place of refuge, or if escape is not a viable option, continued functioning in place as necessary. The latter situation includes occupants who are not mobile or whose egress is prohibited for a variety of reasons, e.g., from an aircraft in flight. The time from initiation of a fire to the point when tenability is compromised such that acceptable performance is not possible is a central component of fire safety design.

The time required to reach compromised tenability may depend upon each occupant's location and movement, along with numerous other characteristics specific to the occupant (see A.2.2). As a result, each occupant may have a different time to compromised tenability. Guidance for consideration of these factors is provided in other sources, e.g., ISO/TR 13387-8 and ISO/TR 16738.

Each occupant may also have a different time to compromised tenability, depending on their particular exposure to heat and fire effluent combustion products and their individual susceptibility to such exposures (see A.2.3). The purpose of the methodology described in this International Standard is to provide a framework for use in estimating the time at which compromised tenability may occur.

The methodology described cannot be used *alone* to evaluate the overall fire safety performance of specific materials or products and cannot, therefore, constitute criteria for a test method. Rather, the equations are to be used as input to a fire hazard or risk analysis [see ISO/TR 13387 (all parts)]. In such an analysis, the estimated time to compromised tenability also depends on the nature both of the fire (e.g. heat release rate, quantity and types of combustibles, fuel chemistry) and of the enclosure (e.g. dimensions, ventilation). These determine the toxic-gas concentrations, the gas and wall temperatures and the density of smoke throughout the enclosure as a function of time. Furthermore, estimation of exposure is determined, in part, by assumptions regarding the position of the occupants' heads relative to the hot smoke layer that forms near ceilings and descends as the fire grows.

The guidance in this International Standard is based on the best available scientific judgment in using a state-of-the-art but less-than-complete knowledge base of the consequences of human exposure to fire effluents. For ethical reasons, much of the methodology described has not been and cannot be validated experimentally with humans. However, for carbon monoxide, the major contributor to prevention of escape and the most frequent cause of fire fatalities, the database is actually quite extensive and well-validated with human experience.

As with all predictive methodology, uncertainty exists in the application of this International Standard. An estimation of the uncertainty for each procedure is provided, with the user being encouraged to determine the significance of these uncertainties in the estimation of the outcome of a given fire scenario.

Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires

1 Scope

This International Standard is one of many tools available for use in fire safety engineering. It is intended to be used in conjunction with models for analysis of the initiation and development of fire, fire spread, smoke formation and movement, chemical species generation, transport and decay, and people movement, as well as fire detection and suppression. This International Standard is to be used only within this context.

This International Standard is intended to address the consequences of human exposure to the life-threatening components of fire. The time-dependent concentrations of fire effluents and the thermal environment of a fire are determined by the rate of fire growth, the yields of the various fire gases produced from the involved fuels, the decay characteristics of those fire gases and the ventilation pattern (see A.1). Once these are determined, the methodology presented in this International Standard can be used for the estimation of the time at which individuals can be expected to experience compromised tenability.

With care, this guidance can also be applied to estimation of the time limit for rescuing people who are immobile due to injury, medical condition, etc.

This International Standard establishes procedures to evaluate the life-threatening components of fire hazard analysis in terms of the status of exposed human subjects at discrete time intervals. It makes possible the estimation of the time at which occupants can experience compromised tenability (see A.2). It enables estimation of a compromised tenability endpoint for each of the fire effluent components, with the most important endpoint being the earliest to occur.

Although the concept of compromised tenability is consistent with the definition of incapacitation (see ISO 13943), the latter term is not used in this International Standard due to its potentially broad interpretation to include many effects, including collapse and unconsciousness, that are not addressed. This International Standard focuses specifically on compromised tenability as influenced by both physiological and behavioural responses resulting from exposure to a fire's life-threatening components.

The life-threatening components addressed include fire-effluent toxicity, heat, and visual obscuration due to smoke. In cases where the effluent composition is available, the toxic gas model is to be used for assessment of fire-effluent toxicity. For those cases where the effluent composition is unknown, an additional mass-loss model using generic toxic potency values is provided.

2 Normative references

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

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following apply.

3.1
tenability
ability of humans to perform cognitive and motor-skill functions at an acceptable level when exposed to a fire environment

NOTE If exposed individuals are able to perform cognitive and motor-skill functions at an acceptable level, the exposure is said to be tenable. If not, the exposure is said to result in compromised tenability.

4 General principles

4.1 Time to compromised tenability

The time to compromised tenability for individuals is the shortest of four distinct times estimated from consideration of asphyxiant fire gases, irritant fire gases, heat, and visual obscuration due to smoke.

The context and mechanisms of the fire-effluent toxicity component of life threat are discussed in Annex A. Effects of the asphyxiant toxicants, carbon monoxide and hydrogen cyanide (see A.3), as well as those of eye and upper-respiratory tract sensory irritants (see A.4), are described in detail.

Responses to these exposures involve functions of the human cardiovascular, respiratory and neurological systems that are dependent upon inherent physical characteristics (e.g., age, body weight, pre-existing cardiopulmonary conditions), along with environmental considerations and physical activity at the time of exposure. As a result, individual human responses can be highly variable and, therefore, not readily reduced to usable engineering equations for prediction of compromised tenability without considerable simplification, application of numerous assumptions, and exclusion of unusual circumstances.

With regard to the susceptibilities of individuals to the insults of fire exposure, a primary assumption of this International Standard is that all occupant responses are treated as an *a priori* log-normal statistical distribution with respect to a median time, with half of the population experiencing a tenable exposure and half experiencing compromised tenability (see 5.3). Other statistical distributions are possible, but in the absence of actual data, the log-normal is the most defensible.

4.2 Toxic-gas model

4.2.1 The toxic-gas models described in this International Standard address effects that are considered detrimental to human tenability. Because they are physiologically unrelated and mechanistically independent, asphyxiant toxicants and irritant toxicants are treated separately (see A.3 and A.4).

With irritant toxicants, only those that cause eye and upper-respiratory tract sensory irritation are considered in this International Standard as having effects on tenability (see A.4.2). Serious effects of pulmonary irritation are manifested from a few hours up to several days after exposure and are not normally expected to have a direct impact on tenability (see A.4.3).

4.2.2 The basic principle for estimating the asphyxiant component of toxic hazard analysis involves the exposure dose of each toxicant, i.e. the integrated area under each concentration-time curve. Fractional effective doses (FEDs) are determined for each asphyxiant at each discrete increment of time. The time at which their accumulated sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria.

4.2.3 The basic principle for estimating the eye and upper respiratory tract sensory irritant component of toxic hazard analysis involves the concentration of each irritant. Fractional effective concentrations (FECs) are determined for each irritant at each discrete increment of time. The time at which their sum exceeds a specified threshold value represents the time to compromised tenability relative to the chosen safety criteria.

4.3 Mass-loss model

The mass-loss model provides for a simplified estimation of the time to occupants' compromised tenability by using total fire-effluent lethal toxic potency data obtained from laboratory test methods (ISO 13344). However, it does not distinguish between the toxic effects of different fire effluent components. The basic principle involves the exposure doses of the fire effluents produced from materials and products, i.e. the integrated areas under their concentration-time curves. FEDs are determined for fire effluents at each discrete increment of time. The time at which their accumulated sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria.

4.4 Heat and radiant energy model

Heat and radiant energy are assessed using an FED model analogous to that used for fire gases. The time at which the accumulated sum of fractional doses of heat and radiant energy exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria.

4.5 Smoke-obscuration model

At some degree of smoke density, occupants can no longer visually discern boundaries and become unaware of their location relative to doors, walls, windows, etc., even if they are familiar with the premises. When this occurs, occupants who may be attempting to escape or perform tasks can become so disoriented that their tenability is compromised. The model is based on the concept of minimum detectable contrast, i.e. the minimum visible brightness difference between an object and a background.

NOTE For occupants who are not engaged in cognitive or motor-skill activity, smoke obscuration, alone, should not compromise tenability.

4.6 Assumptions and exclusions

a) Asphyxiant toxicants, irritants, heat and visual obscuration are each considered as acting independently. Some degrees of interaction between these insults are known to occur (see A.6), but are considered secondary.

b) Asphyxiant toxicants are known to increase somewhat the respiratory rate of exposed occupants, followed by a decrease in respiratory rate as narcosis begins to occur. Resulting fluctuations of toxicant uptake due to these effects are considered secondary.

c) Exposed occupants are considered to be at relatively normal ambient environmental conditions and at altitudes below which reduced oxygen could be a factor, and performing at a moderate level of physical activity. Deviation from these conditions can affect susceptibility, but supporting quantitative data are scarce.

d) The effects of aerosols and particulates and any interactions with gaseous fire-effluent components are not considered. The physical form of toxic effluents is known to have some influencing effects, but in this International Standard they are considered secondary to the direct effects of vapour-phase effluents.

e) Adverse health effects subsequent to exposure to fire atmospheres are not considered, although it is recognized that they occur. Pre-existing health conditions may be exacerbated and potentially life-threatening sequelae may develop from exposure both to asphyxiants and to pulmonary irritants (see A.3 and A.4.3). Lower respiratory tract effects are typically manifested at time scales much longer than those of the actual fire and, although noted, are not considered in the requirements of this International Standard.

f) The early impacts of visual obscuration due to smoke (e.g., recognition that a fire exists, seeing exit paths clearly) are behavioural in nature and are not included. However, smoke obscuration of such severity that occupants become disoriented places a limitation on the time during which escape may be attempted and is considered.

The equations in the methodology described in this International Standard enable estimation of the status of exposed occupants at discrete time intervals throughout the progress of a fire scenario, up to the time at which such exposure can result in compromised tenability. Should the estimated time be deemed excessively limiting, a variety of protection strategies then require consideration by the fire safety professional.

5 Significance and use

5.1 The objective of this International Standard is to provide simplified, but robust, guidance for engineers in estimating occupants' time to compromised tenability as part of an assessment of a structure's fire safety capabilities when subjected to generalized design fire conditions. Such estimation of occupants' tenability ultimately involves their ability to perform cognitive and motor-skill functions at an acceptable level. Generally, acceptable performance may include any of a number of desirable outcomes, including escape to a place of refuge, or if escape is not a viable option, continued functioning in place as necessary.

NOTE If escape to a place of refuge is the outcome to be considered, the time to compromised tenability may reasonably be equated to the available safe escape time (ASET).

5.2 Operating under a considerable number of simplifying assumptions, this International Standard deals with responses of the overall population as represented by a statistical distribution. It is not intended to provide guidance for a detailed assessment of the insult to specific individuals that might be exposed to a given fire atmosphere — such as is commonly required in forensic investigations. Furthermore, the focus of this International Standard is on assessment of an occupant's tenability, while forensic investigations generally focus on the consequences of compromised tenability. These are quite different objectives. Forensic investigations can also be extremely complicated, involving detailed characterization of specific exposed occupants, along with interpretive expertise far beyond that which can reasonably be taught in a guidance standard.

5.3 The concepts of FED[1] and FEC[2] are fundamental to the methodology of this International Standard. Both concepts relate to the manifestation of physiological and behavioural effects exhibited by exposed subjects.

5.4 The variability of human responses to toxicological insults is best represented by a statistical distribution that takes into account varying susceptibility to the insult. Some people are more susceptible than the average, while others may be less susceptible (see A.5). In this International Standard, FED and/or FEC values of 1,0 correspond, by definition, to the median value of a log-normal distribution of responses, with one-half of the population being less susceptible and one-half being more susceptible. This means that, statistically, 50% of the population would be expected to experience tenable conditions (able to perform cognitive and motor-skill functions at an acceptable level), with 50% then expected to experience compromised tenability (unable to perform cognitive and motor-skill functions at an acceptable level).

Recognizing that threshold criteria of 1,0 FED and/or FEC statistically serve to protect only one-half of the population, users of this International Standard shall use reduced FED and/or FEC threshold criteria in order to satisfy more conservative fire safety objectives. This International Standard provides the flexibility to choose FED and/or FEC threshold criteria as may be appropriate. Guidance is provided in A.5.2. Whatever the rationale used when choosing FED and FEC threshold criteria, it is necessary to use a single value for both FED and FEC in a given estimation of the time to compromised tenability.

5.5 The exposure of occupants to tenable conditions should not be construed as equating to no post-exposure harm. Exposure to fire-gas toxicants that do not cause compromised tenability can still result in a variety of effects that may prolong escape and thus increase exposure intensity to fire effluents and lead to post-exposure health problems; see Annex A. However, quantification of these effects, especially under conditions where effective post-traumatic measures are common practice through medical intervention, is beyond the scope of this International Standard.

5.6 The time-dependent concentrations of fire effluents to which occupants, who are often on the move, are exposed can only be determined using computational fire models and/or a series of real-scale experiments. It is not valid to insert the concentrations of fire effluents or values of smoke optical density obtained from bench-scale test methods in the equations presented in this International Standard.

5.7 The methodology described for toxic gas exposures cannot be validated with people. It is necessary to recognize that uncertainty exists in the precision of the experimental data upon which the equations are based, the representation of those data by algebraic functions, the accuracy of assumptions regarding non-interaction of fire gases with each other and with heat, the susceptibility of people relative to that of test animals, etc.

These uncertainties are estimated in the following sections. As with any engineering calculation, uncertainties should be included in the estimation of the overall uncertainty of a fire hazard or risk analysis. This enables the user to determine whether the difference between the outcomes of two such analyses are truly different or are irresolvable.

NOTE The resulting uncertainty in the estimated time to compromised tenability depends in a non-linear manner upon the uncertainty in the FED and FEC calculations (for instance, these uncertainties can have reduced impact on the estimated outcome of rapidly developing fires).

5.8 There is very little reliable information on asphyxiant gas exposures of less than 1 min or longer than 1 h. Thus, the accuracy of the equations in this International Standard and the resulting estimations for either very short or very long fire scenarios are uncertain. Due to these uncertainties, estimations of time available to escape of less than 1 min are to be reported as <1 min, with caution exercised when making estimations that involve occupant exposures longer than 1 h.

NOTE Due to the uncertainties involved, differences between comparative estimations of time to compromised tenability of less than 1 min are typically insignificant.

6 Toxic-gas models

6.1 Asphyxiant-gas model

6.1.1 Fractional effective doses (FEDs) are determined for each asphyxiant at each discrete increment of time. The time at which their accumulated sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria (see 5.3). The principle of the model in its simplest form for calculating the fractional effective dose, X_{FED}, is shown in Equation (1):

$$X_{\text{FED}} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(C \cdot t)_i} \Delta t \tag{1}$$

where

C_i is the average concentration, expressed in μl·l^{-1}, of an asphyxiant gas "i" over the chosen time increment;

Δt is the chosen time increment, expressed in minutes;

$(C{\cdot}t)_i$ is the exposure dose causing occupants' compromised tenability, expressed in minutes multiplied by μl·l^{-1}.

In estimating incremental effects, ΔX_{FED}, on the fractional effective doses (FEDs), X_{FED}, for each discrete increment of time, Δt, $C_i = C$, and Equation (1) reduces to:

$$X_{\text{FED}} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{1}{t_i} \cdot \Delta t \tag{1a}$$

where the time, t_i, to compromised tenability due to component "i" is a function of its concentration, with the units of time cancelling to give a dimensionless fraction for X_{FED}.

For carbon monoxide:

$$t_{CO} = \frac{35\ 000}{\varphi_{CO}}$$

where φ_{CO} is the average concentration, expressed in μl·l^{-1}, of CO over each time increment, Δt, in minutes.

NOTE The compromising tenability dose, $(C{\cdot}t)$, for CO of 35 000 μl·l^{-1}min was obtained from experiments on juvenile baboons subjected to an escape paradigm[3]. Using the Stewart–Peterson equation[4], a dose of 35 000 μl·l^{-1}min would produce approximately 30 % blood carboxyhaemoglobin saturation in humans having average adult body weight and a respiratory minute volume of 20 l/min.

For hydrogen cyanide:

$$t_{HCN} = 1{,}2 \times 10^{6} \times \varphi_{HCN}{}^{-2{,}36}$$

where φ_{HCN} is the average concentration, expressed in μl·l^{-1}, of HCN over each time increment, Δt, in minutes.

NOTE The compromising tenability dose for HCN cannot be represented as a constant. Because of this, the exponential expression shown was derived as a best fit to data obtained from studies on cynomolgus monkeys[2], with the shape of the curve modified for extrapolation to higher and lower concentrations based on rodent data. The results are consistent with human responses to the extent that they are known.

6.1.2 Equation (1) thus expands to Equation (2) for determination of FED values due to carbon monoxide (CO) and hydrogen cyanide (HCN).

$$X_{FED} = \sum_{t_1}^{t_2} \frac{\varphi_{CO}}{35\ 000} \Delta t + \sum_{t_1}^{t_2} \frac{\varphi_{HCN}{}^{2{,}36}}{1{,}2 \times 10^{6}} \Delta t \qquad (2)$$

where

φ_{CO} is the average concentration, expressed in μl·l^{-1}, of CO over the time increment, Δt;

φ_{HCN} is the average concentration, expressed in μl·l^{-1}, of HCN over the time increment, Δt;

Δt is the time increment, expressed in minutes.

It is estimated that the uncertainty in Equation (2) is ± 35 % based on the information in Notes 1 to 5.

NOTE 1 All available evidence supports the working hypothesis that, in typical fire atmospheres, CO and HCN are the only asphyxiant combustion products that exert a significant effect on the time to compromised tenability. Oxygen vitiation can also produce asphyxiation, but its consideration is not required as long as O_2 concentrations do not fall below 13 %. (The user is referred to Reference [2] for consideration of O_2 concentrations less than 13 %.) The narcotic effect of CO_2 is not significant at the concentrations experienced in otherwise tenable fire atmospheres. The increased rate of asphyxiant uptake due to hyperventilation caused by CO_2 is addressed in 6.1.3.

NOTE 2 The dose-effect data used here are based on both human and non-human primate experience. Carbon monoxide and hydrogen cyanide have identical pathological mechanisms both in laboratory animals and in humans. Species-specific metabolisms that can modulate the toxic potency of these agents are not known. The dose rate, i.e. kinetics of uptake, is commonly higher for small animals when compared to humans, because the higher energy consumption of the former requires a higher ventilation per unit of body mass. It is, therefore, considered adequately conservative that no adjustment in FED values be made to reflect interspecies differences in susceptibility.

NOTE 3 Guidance on analytical methods for measuring φ_{CO} and φ_{HCN} is given in ISO 19701 and ISO 19702.

NOTE 4 A moderate level of physical activity, equivalent to brisk walking on a level surface, is assumed. Guidance appropriate for other levels of activity is available [2].

NOTE 5 It is assumed that heat and irritant gases have no effect on the FED for asphyxiants. Although some effects are likely, no quantitative information is available. Any interactive effects are considered to be secondary.

6.1.3 The terms containing φ_{CO} and φ_{HCN} in Equation (2) at each time increment are to be multiplied by a frequency factor, v_{CO_2}, to allow for the increased rate of asphyxiant uptake due to hyperventilation[2].

$$v_{CO_2} = \exp\left[\frac{\varphi_{CO_2}}{5}\right] \tag{3}$$

where φ_{CO_2} is the average volume percent of CO_2 during the time increment.

NOTE Equation (3) is derived from an empirical fit to human hyperventilation, corrected for uptake inefficiencies in the lung. It is accurate to within ± 20 %.

6.2 Irritant-gas model

6.2.1 The effects of eye and upper-respiratory tract sensory irritants are estimated using the FEC concept shown in Equation (4)[2]. As a first-order assumption, direct additivity of the effects of the different irritant gases is employed. It is also assumed that the concentration of each irritant gas reflects its presence totally in the vapour phase. Fractional effective concentrations (FECs) are determined for each irritant at each discrete increment of time. The time at which their sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria (see 5.3).

$$X_{FEC} = \frac{\varphi_{HCl}}{F_{HCl}} + \frac{\varphi_{HBr}}{F_{HBr}} + \frac{\varphi_{HF}}{F_{HF}} + \frac{\varphi_{SO_2}}{F_{SO_2}} + \frac{\varphi_{NO_2}}{F_{NO_2}} + \frac{\varphi_{acrolein}}{F_{acrolein}} + \frac{\varphi_{formaldehyde}}{F_{formaldehyde}} + \sum \frac{\varphi_{irritant}}{F_{C_i}} \tag{4}$$

where

φ is the average concentration, expressed in μl·l^{-1}, of the irritant gas;

F is the concentration, expressed in μl·l^{-1}, of each irritant gas that is expected to seriously compromise occupants' tenability.

F_{HCl}	1 000 μl·l^{-1}	F_{NO_2}	250 μl·l^{-1}
F_{HBr}	1 000 μl·l^{-1}	$F_{acrolein}$	30 μl·l^{-1}
F_{HF}	500 μl·l^{-1}	$F_{formaldehyde}$	250 μl·l^{-1}
F_{SO_2}	150 μl·l^{-1}		

It is estimated that the uncertainty associated with the use of Equation (4) is ± 50 %. This could be significantly larger if the products involved in the fire generate toxicologically important quantities of additional irritants; see 6.2.2.

NOTE 1 Eye and upper-respiratory tract sensory irritation are direct and occur at the first contact of an inhaled irritant with susceptible tissues; see A.4.2. Although an equilibration with the lining fluids of mucous membranes appears to occur in a time-dependent manner at low to moderate concentrations, it is short compared to the time to effect for the other limits to compromised tenability and appears to be negligible at higher concentrations. Therefore, this International Standard considers eye and upper-respiratory tract sensory irritant effects to be instantaneous and concentration dependent, with use of the FEC (rather than the FED) considered as the appropriate option with such exposures.

NOTE 2 Establishment of F-factors expected to seriously compromise the tenability of exposed occupants was obtained from analysis of relevant data cited in References [5] to [13].

NOTE 3 Guidance on analytical methods for these gases is given in ISO 19701 and ISO 19702.

6.2.2 Numerous other irritant species can be formed in fires. The range of other effluent species selected for analysis shall be broad enough to cover those species of toxicological significance that can reasonably be expected to be released, based on the knowledge of the composition of the material and in consultation with published documentation for exposure criteria for use in Equation (4).

NOTE Such irritants include, but are not limited to, isocyanates, aldehydes, nitriles, sulfur compounds and phosphorus compounds.

7 Mass-loss model

7.1 Concentrations of fire-gas toxicants as a function of time cannot readily be determined in many cases. The basic FED concept can still be employed using mass loss, the volume into which fire effluents are dispersed and lethal toxic potency values as determined from laboratory test methods, e.g. ISO 13344.

7.2 The value of C_i for the concentration of fire effluent produced from material or product "*i*" is related to the mass loss and the volume into which the fire effluent is dispersed as shown in Equation (5):

$$C_i = \frac{\Delta m}{V} \tag{5}$$

where

Δm is the mass loss, expressed in grams;

V is the volume, expressed in cubic metres.

7.3 Substitution of Equation (5) into Equation (1) yields Equation (6), which is now a mass-loss model (see Note), rather than one for toxic gases.

$$X_{\mathrm{FED}} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{\Delta m_{\mathrm{aa}}}{V\left(C \cdot t\right)_i} \Delta t \tag{6}$$

where

Δm_{aa} is the average accumulated mass loss, expressed in grams, over the time increment, Δt;

V is the volume, expressed in cubic metres;

Δt is the time increment, expressed in minutes;

$(C \cdot t)_i$ is one half of the value of $(\mathrm{LCt}_{50})_i$, expressed as minutes × grams per cubic metre.

Care should be taken that the conditions under which laboratory test LCt_{50} data were obtained are relevant to the type of fire being considered (ISO 19706, ISO 13344).

One half of the LCt_{50} is recommended as an approximate exposure dose when relating compromised tenability to lethality [14], [15]. Although based on experimental data obtained from exposure of rats, this relationship is also expected to be appropriate for human exposure. It should be recognized that LC_{50} or LCt_{50} values for fire effluents may also include the effects of pulmonary irritants, but not those of eye and upper-respiratory tract sensory irritants that can impact tenability (see 4.2.1).

NOTE The mass-loss model represents a considerable simplification for assessment of the life threatening effects of fire effluents. It does not distinguish between the different effects of individual fire gases, but derives an estimate of toxic potency from the overall lethal effects of a toxic effluent mixture, the composition of which depends on the material or product decomposed in a laboratory test method and the thermal decomposition conditions in a test. The results from such tests provide an estimate of lethal toxic potency related to a 30-min exposure period and a 14-d post-exposure observation period. The lethal toxic potency estimate, therefore, includes lethality both during and after exposure. When the data are derived from methods described in ISO 13344, the toxic potency data represent estimated lethal toxic potencies for specified gas mixtures. When the data are derived from animal exposures, they represent the total lethal effects of the effluent mixture, including any interactions between all known and unknown individual toxic agents present, as well as effects related to the physical form of the effluent in terms of gases and particulates. When several different materials are involved in a fire, the toxic potencies of the effluent from each material are assumed to be directly additive in relation to the estimated mass loss concentrations in the fire enclosure as a function of time.

7.4 Combustible fuel in a fire often consists of a mixture of materials and products that may be unidentified as to their nature and relative quantity. In these cases, a "generic" LCt_{50} value may be employed, i.e. 900 $\mathrm{g \cdot m^{-3} \cdot min}$ for well-ventilated, pre-flashover fires and 450 $\mathrm{g \cdot m^{-3} \cdot min}$ for vitiated post-flashover fires [16]. These values are consistent with analysis of data obtained from laboratory tests on a variety of materials and products [16]. For occupants' compromised tenability, $(C{\cdot}t)_i$ in Equation (6) then becomes 450 $g{\cdot}m^{-3}{\cdot}min$ for well-ventilated pre-flashover fires and 220 $g{\cdot}m^{-3}{\cdot}min$ for vitiated post-flashover fires.

NOTE The vitiated post-flashover exposure dose of 220 $g{\cdot}m^{-3}{\cdot}min$ for occupants' compromised tenability provides for their exposure to 38 000 $\mu l{\cdot}l^{-1}{\cdot}min$ of CO (assuming a CO yield of 0,2). Using the Stewart−Peterson equation [4], a dose of 38 000 $\mu l{\cdot}l^{-1}{\cdot}min$ would be expected to result in approximately 34 % carboxyhaemoglobin (COHb) saturation in humans having a respiratory minute volume of 20 l/min (compare with 6.1.2, Note 2).

Uncertainties in calculations associated with using the pre-flashover and post-flashover values for occupants' compromised tenability are estimated to be ± 75 % and ± 30 %, respectively.

It is cautioned that "generic" LCt_{50} values represent only an approximation. Their use is subject to appropriate sensitivity analyses, as well as to expert toxicological and engineering judgment.

7.5 FEDs are determined for fire effluents at each discrete increment of time. The time at which their accumulated sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria; see 5.3.

8 Heat

8.1 There are three basic ways in which exposure to heat can lead to life threat:

a) hyperthermia;

b) body surface burns;

c) respiratory tract burns.

For use in the modelling of life threat due to heat exposure in fires, it is necessary to consider only two criteria:

— threshold of second degree burning of the skin;

— exposure where hyperthermia is sufficient to cause mental deterioration and, therefore, threaten survival.

NOTE Thermal burns to the respiratory tract from inhalation of air containing less than 10 % by volume of water vapour do not occur in the absence of burns to the skin or the face; thus, tenability limits with regard to skin burns are normally lower than for burns to the respiratory tract. However, thermal burns to the respiratory tract can occur upon inhalation of air above 60 °C when saturated with water vapour.

8.2 The tenability limit for exposure of skin to radiant heat is approximately 2,5 $kW{\cdot}m^{-2}$. Below this incident heat flux level, exposure can be tolerated for 30 min or longer without significantly affecting tenability. Above this threshold value, the time, t_{Irad}, expressed in minutes, to second degree burning of skin due to radiant heat decreases rapidly according to Equation (7)[17]:

$$t_{\mathrm{Irad}} = 6{,}9\, q^{-1{,}56} \tag{7}$$

where q is the radiant heat flux, expressed in kilowatts per square metre.

As with toxic gases, an exposed occupant may be considered to accumulate a dose of radiant heat over a period of time. The FED of radiant heat accumulated per minute is the reciprocal of t_{Irad}.

NOTE Radiant heat tends to be directional, producing localized heating of particular areas of skin even though the air temperature in contact with other parts of the body can be relatively low. Skin temperature depends upon the balance between the rate of heat applied to the skin surface and the removal of heat subcutaneously by the blood. Thus, there is a threshold radiant flux below which significant heating of the skin is prevented but above which quite rapid heating occurs.

The time to experiencing pain due to radiant heat can have a behavioural effect on the time to compromised tenability. The time, t_{Irad}, expressed in minutes, to experiencing pain due to radiant heat is a somewhat more strongly inverse function of radiant heat than that for the burning of skin. It is expressed by Equation (8) [17]:

$$t_{\mathrm{Irad}} = 4{,}2\,q^{-1{,}9} \tag{8}$$

where q is the radiant heat flux, expressed in kilowatts per square metre.

Based on the above information, it is estimated that the uncertainty associated with the use of Equations (7) and (8) is ± 25 %. Moreover, an irradiance of 2,5 kW·m^{-2} would correspond to a source surface temperature of approximately 200 °C, which is most likely to be exceeded near the fire, where conditions are changing rapidly.

8.3 Calculation of the time to prevention of escape under conditions of exposure to convective heat from air containing less than 10 % by volume of water vapour can be made using either Equation (9)[18] or Equation (10)[2].

As with toxic gases, an exposed occupant can be considered to accumulate a dose of convected heat over a period of time. The FED of convected heat accumulated per minute is the reciprocal of t_{Iconv}.

8.3.1 The time, t_{Iconv}, expressed in minutes, to experiencing pain due to convected heat accumulated per minute depends upon the extent to which an exposed occupant is clothed and the nature of the clothing. For fully clothed subjects, Equation (9) is appropriate[18]:

$$t_{\mathrm{Iconv}} = (4{,}1 \times 10^{8})\,T^{-3{,}61} \tag{9}$$

where T is the temperature, expressed in degrees Celsius.

8.3.2 For unclothed or lightly clothed subjects, it is more appropriate to use Equation (10)[2].

$$t_{\mathrm{Iconv}} = (5 \times 10^{7})\,T^{-3{,}4} \tag{10}$$

where the variables are the same as for Equation (9).

Equations (9) and (10) are empirical fits to human data. It is estimated that the uncertainty is ± 25 %.

NOTE Thermal tolerance data for unprotected skin of humans suggest a limit of about 120 °C for convected heat, above which there is, within minutes, the onset of considerable pain along with the production of burns[2]. Depending upon the length of exposure, convective heat below this temperature can also cause hyperthermia.

8.4 The body of an exposed occupant may be regarded as acquiring a “dose” of heat over a period of time. A short exposure to a high radiant-heat flux or temperature is generally less tolerable than a longer exposure to a lower temperature or heat flux. A methodology based on additive FEDs similar to that used with toxic gases may be applied and, providing that the temperature experienced by the occupant is stable or increasing, the total fractional effective dose of heat acquired during an exposure can be calculated using Equation (11):

$$X_{\mathrm{FED}} = \sum_{t_1}^{t_2} \left(1/t_{\mathrm{Irad}} + 1/t_{\mathrm{Iconv}}\right)\Delta t \tag{11}$$

In areas within an occupancy where the radiant flux to the skin is under 2,5 kW·m^{-2}, the term ($1/t_{\mathrm{Irad}}$) in Equation (11) is set at zero.

The uncertainty associated with the use of Equation (11) is dependent upon the uncertainties with the use of Equations (7), (8), (9) and (10).

8.5 In the same manner as with toxic-gas exposures, the time at which the FED accumulated sum exceeds a specified threshold value represents the time to compromised tenability relative to chosen safety criteria; see 5.3.

9 Smoke-obscuration model

The principle of the smoke-obscuration model is based on the concept of minimum detectable contrast, i.e. the minimum visible brightness difference between an object and a background. It is estimated that occupants literally cannot see their hands in front of their faces, thus becoming disoriented. The time at which this mass loss concentration is reached represents that after which occupants' tenability may be compromised.

NOTE 1 Visual contrast, c_V, is given by Equation (12) [19].

$$\ln c_V = -\sigma \rho_{sm} \cdot L \quad (12)$$

where

σ is the mass specific extinction coefficient, in square metres per gram, for smoke aerosol;

ρ_{sm} is the mass concentration of smoke aerosol, expressed in grams per cubic metre;

L is the smoke-filled distance, expressed in metres, between an object and the viewer.

Symbols used here have been modified from those contained in Reference [19].

Using a minimum detectable contrast of 0,02 [19], and a generic value of σ (corrected for white light) for well-ventilated fire smoke of 10 $m^2 \cdot g^{-1}$ [20], it is calculated from Equation (13) that occupants cannot see more than a distance of approximately 0,5 m (about an arm's length) at a mass concentration of light-obscuring smoke aerosol of 0,8 $g \cdot m^{-3}$.

Equation (13) can be used to convert the mass concentration of smoke aerosol to the corresponding mass loss concentration produced from the burning fuel in a fire:

$$\rho_{bf} = \frac{\rho_{sm}}{W_{sa}} \quad (13)$$

where

ρ_{bf} is the mass loss concentration of burning fuel, expressed in grams per cubic metre;

ρ_{sm} is the smoke mass concentration, expressed in grams per cubic metre;

W_{sa} is the yield of smoke aerosol from the fuel given by Equation (14):

$$W_{sa} = \frac{m_a}{m_{fc}} \quad (14)$$

where

m_a is the mass of the aerosol, expressed in grams;

m_{fc} is the mass, expressed in grams, of fuel consumed.

For well-ventilated flaming fires, a number of common plastics have aerosol yields of 1 % to 10 %, with wood being somewhat lower. Although there is considerable scatter in the measurements, 4 % represents a typical yield, with a smoke aerosol mass concentration of 0,8 $g \cdot m^{-3}$ then equating to a fuel mass loss concentration of about 20 $g \cdot m^{-3}$. For under-ventilated flaming measurements in a small-scale device, the aerosol yields appear to double (with an uncertainty of $\pm$ 50 % [21]) and the yield from wood cribs increases into the same range as for plastics [22]. Thus for under-ventilated combustion, a smoke aerosol mass concentration of 0,8 $g \cdot m^{-3}$ equates to a fuel mass loss concentration of about 10 $g \cdot m^{-3}$. The change in the value of σ is small compared to the change in yield and is neglected.

NOTE 2 Experiments have shown that the threshold of visibility for light-reflecting signs occurs at an aerosol mass concentration of approximately 0,3 $g \cdot m^{-3} \cdot L^{-1}$ and, for light-emitting signs, at approximately 0,8 $g \cdot m{-}3 \cdot L^{-1}$, where L is equal to distances of 5 m to 15 m [23]. The former value is recommended for assessing the visibility of stairs, doors, walls, etc. Assuming that the relationship holds at the shorter distance of 0,5 m (about an arm's length), it yields a threshold aerosol mass concentration of 0,6 $g \cdot m^{-3}$, above which occupants' tenability may be compromised. This is within reasonable agreement with the concept.

NOTE 3 In many large- and small-scale tests, smoke is measured in terms of optical obscuration. This aerosol mass concentration of 0,8 g·m^{-3} over a path length of 0,5 m corresponds to a smoke optical density of 1,7. Smoke optical density is defined as $\log_{10}(I_0/I)$, the logarithm of the transmitted light to the emitted or reflected light from a source, and is equal to $-\sigma\rho_{sm}L/2{,}3$ [see Equation (12) for definition of symbols].

NOTE 4 The best value for a mass loss concentration of smoke estimated to compromise occupants' tenability is 20 g·m^{-3} for well-ventilated fires and 10 g·m^{-3} for under-ventilated fires. The uncertainty in these values is estimated to be plus or minus a factor of two. This reflects

a) the wide variation among measurements of smoke-yield data for a given material,

b) the differences in smoke yields for different materials,

c) the fact that an extrapolation of the experimental findings to short distances has not been validated.

When the fire involves a single material for which the aerosol yield has been measured under combustion conditions germane to that fire, this uncertainty is significantly smaller.

NOTE 5 The equivalent of people who are more susceptible to effects from the inhalation of gases are people whose vision is less precise, i.e. who require a higher degree of contrast to discern an object against a background. There are no data indicating what "exposure factor" provides for the susceptible population in a manner equivalent to that in A.5.2 for exposure to fire gases. However, using the same factor of 0,3 and recognizing the logarithmic dependence of Equation (12), the resulting escape-preventing concentration of smoke for this population would be 15 g·m^{-3} for well-ventilated fires and 7 g·m^{-3} for under-ventilated fires with the uncertainty estimated to be plus or minus a factor of two.

10 Report

The report shall include the following information for each fire scenario to be assessed:

a) time, expressed in minutes, to compromised tenability from a fire calculated independently for each of the components evaluated using the described methodology for asphyxiant gases, irritant gases, mass loss, heat and smoke obscuration as well as the following details:

   1) identification of all fire gases considered, including rationale for those chosen,

   2) the safety criterion and associated threshold value selected for each component,

   3) any additional assumptions made in the calculations;

b) the estimated time to compromised tenability for each component, as well as the identification of that which is the shortest (including consideration of uncertainties that may result in the time to compromised tenability being limited by multiple components). For occupants not involved in cognitive or motor function activities, identification of the shortest time shall not include consideration of smoke obscuration.

Annex A
(informative)

Context and mechanisms of toxic potency

A.1 Elements of fire hazard analysis

Figure A.1 gives the flowchart of the different elements which are necessary to analyse for a fire hazard.

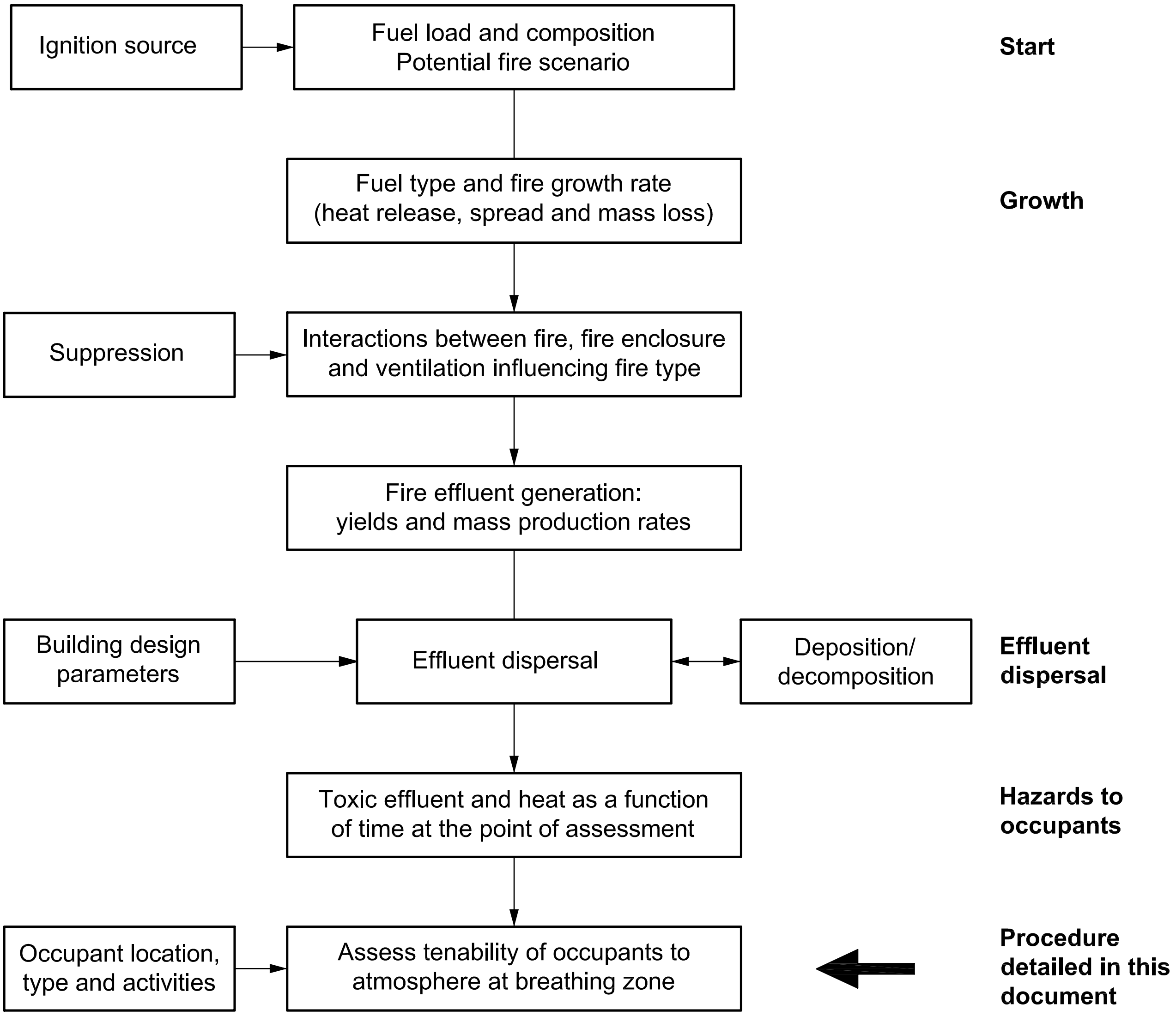

Figure A.1 — Factors in determining the tenability of occupants to fire hazard

A.2 Compromised tenability

A.2.1 General

There are both behavioural and physiological effects associated with exposure to fire and fire effluents that can impact significantly upon occupants' tenability being compromised.

A.2.2 Behavioural effects

Behavioural effects are commonly organized into four human factor areas, including occupant characteristics, responses to cues, decision-making, and movement. These human factors have been examined in detail in ISO/TR 16738 and other guidance documents [24]. However, for overall tenability, it is also necessary to consider the ways in which human behaviour would be modified by exposure to fire and its combustion products. These include reduced visibility, hyperthermia and impaired breathing due to upper-respiratory tract sensory irritation. At lower levels of exposure, these effects may impact more upon occupants' possible courses of action and other manifestations of their perception of relative risks. However, at higher levels, the behavioural consequences of such exposure could lead to compromised tenability.

A.2.3 Physiological effects

There are a number of primary physiological effects of exposure to fire and its combustion products. These can include visual obscuration due to smoke optical density, lachrymation and reflex blinking of the eyes, pain in the eyes, nose, throat and chest, breath-holding, coughing, laryngeal spasms, bronchoconstriction and dyspnea (inability to breathe) — all due to eye and upper-respiratory tract irritation — in addition to hyperthermia and thermal burns, and various types of hypoxia due to lack of oxygen supplied to critical body organs. Hypoxia results in central nervous system depression, the effects of which are manifest by varying degrees of impaired judgement, disorientation, decreased ability to perform aerobic work, loss of motor coordination, unconsciousness and, ultimately, death. Collectively, these physiological effects can all impact upon the time to compromised tenability.

A.3 Asphyxiant toxicants

A.3.1 General

An asphyxiant is a toxicant causing hypoxia, a decrease in oxygen supplied to, or utilized by, body tissue, resulting in central-nervous-system depression with loss of consciousness and, ultimately, death. Effects of these toxicants depend upon accumulated doses, i.e. a function of both concentration and the time or duration of exposure. The severity of the effects increases with increasing dose. Among the fire-gas toxicants, carbon monoxide and hydrogen cyanide have received the most study and are best understood with respect to their ability to compromise tenability and cause death of those exposed [2], [25].

A.3.2 Carbon monoxide

The toxic effects of carbon monoxide (CO) are those of anaemic hypoxia, characterized by a lowered oxygen-delivery capacity of the blood, even when the arterial partial pressure of oxygen and the rate of blood flow are normal. This is due to the affinity of haemoglobin for carbon monoxide being about 250 times greater than for oxygen, resulting in partial saturation of the blood with carboxyhaemoglobin (COHb). The extent to which blood haemoglobin is converted to COHb can readily be measured in a clinical laboratory and is expressed as percent COHb saturation.

The relationship between blood COHb saturation, exposure conditions of CO concentration and time, and volume of air inspired per minute for average adults is empirically approximated in the Stewart–Peterson equation [4]. This equation exhibits a linear dependence of COHb on time and respiratory rate, with a slightly exponential dependence on CO concentration. The Coburn–Forster-Kane equation [26] takes into account additional parameters determining the uptake of CO. It is much more complicated but quite useful for special circumstances, particularly those involving exposure periods exceeding one hour or for persons with bodyweights deviating significantly from an average of 70 kg.

Exposure to carbon monoxide at levels insufficient to cause death or even unconsciousness can result in varying degrees of impaired judgment, disorientation, confusion and diminished physical coordination such that inappropriate actions may be taken. Significant carbon-monoxide exposure can also result in post-exposure neurological damage [27], including encephalopathy and a resulting memory loss. The incidence of such delayed neurological impairment appears to increase with age [28].

Susceptibility of human populations to carbon monoxide intoxication depends on many factors that include both their inherent physical characteristics (age, body weight, pre-existing cardiopulmonary conditions) and activity (oxygen demand) at the time of the exposure; see also A.5.1.

In this International Standard, it is assumed that the human population is comprised of healthy, young adults at a moderate level of activity, with allowances then made for variability due to more susceptible subpopulations. An FED criterion of 1,0, corresponding to the median value of a log-normal distribution of human responses, translates to a blood carboxyheamoglobin saturation of approximately 30 %. Use of a threshold criterion of 0,3 FED (see A.5.2) would reduce the blood carboxyheamoglobin saturation to about 10% as an allowable maximum for acute exposure, above which tenability could potentially be compromised.

A.3.3 Hydrogen cyanide

Approximately 25 times more toxic than carbon monoxide, hydrogen cyanide (HCN) owes its toxic effects to the cyanide ion, which is formed by hydrolysis in the blood. Unlike carbon monoxide, which remains primarily in the blood, the cyanide ion is distributed throughout the body water and is in contact with the cells of tissues and organs. The cyanide ion readily reacts with the enzyme, cytochrome oxidase, which occupies a central role in the utilization of oxygen in practically all cells. Its inhibition rapidly leads to loss of cellular functions (cytotoxic hypoxia), then to cell death. In contrast to carbon monoxide, cyanide does not decrease the availability of oxygen but, rather, prevents the utilization of oxygen by cells, with the heart and brain being particularly susceptible.

Unlike carbon monoxide, the effects of hydrogen cyanide are not essentially linear with respect to its concentration. On the contrary, its effects are a strongly exponential function of its concentration. As a result, a short exposure to a high concentration of hydrogen cyanide is much more hazardous than a long exposure to a lower concentration even though the dose (concentration × time) may be the same.

Forensic investigations involving victims suspected of having been exposed to HCN commonly report blood cyanide concentrations. These can then be used to establish the possible contribution of HCN to the death of the victim. However, again unlike carbon monoxide, blood cyanide concentrations are not readily correlated with exposure conditions of HCN concentration and time (dose). Thus, in this International Standard, criteria for exposure to HCN are not based on blood cyanide but, rather, on an empirical relationship involving time and the exponential dependence of effects on exposure concentration.

A.4 Irritant toxicants

A.4.1 General

In contrast to the systemic effects caused by asphyxiant toxicants, such as CO and HCN, the effects of exposure to irritants are much more complex. Although most fire-effluent irritants produce signs and symptoms of eye, upper-respiratory tract, and deep lung or pulmonary irritation [2], [25], these effects are mechanistically independent and physiologically unrelated. They shall, therefore, be considered separately.

A.4.2 Eye and upper-respiratory tract irritants

A.4.2.1 General

Eye and upper-respiratory tract irritants may produce both concentration-dependent sensory effects and dose-dependent pathological effects [29].

One of the major difficulties in attempting to predict the consequences of exposure to irritants is the scarcity of quantitative human-exposure data. With very few controlled studies having been carried out with humans, most data are only anecdotal, derived from accidental industrial exposures with only a vague knowledge of actual irritant concentrations [2]. Measurements exist for upper-respiratory tract sensory irritation in rats and mice [6] that, when considered along with other relevant data, have led to a systematic evaluation of those concentrations expected to be hazardous for human exposure.

Under the most comprehensive peer-review process ever used to establish short-term limits for acutely toxic chemicals, the National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances developed three levels of safety objectives, one of which relates in part to the objectives of this International

Standard. The AEGL Advisory Committee defines AEGL-2 as "the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape [7]."

Although the latter condition relates to this International Standard, AEGL-2 criteria appear to largely consider dose-dependent pathological effects. Based primarily on comprehensive analysis of rodent data, the AEGL-2 criterion for exposure of humans to hydrogen chloride is, for example, estimated to be 100 $\mu l \cdot l^{-1}$ for exposure periods up to 10 min, with reduced concentrations as appropriate for longer periods of time [7].

Dose-dependent pathological effects of upper-respiratory tract irritants may be initiated during fires. However, their major injurious effects actually occur several hours or even days after the exposure. Since concentration-dependent effects of upper-respiratory tract sensory irritation are manifest much more rapidly than those caused by dose-dependent pathological insult, they are considered more important in influencing time to compromised tenability and are chosen for use in this International Standard. Dose-dependent pathological effects of upper respiratory irritants may, however, be considered as needed along with pulmonary irritation (A.4.3) if post-exposure effects are to be considered.

A.4.2.2 Concentration-dependent sensory effects

In the case of eye and upper-respiratory tract (i.e., nose, throat and larynx) sensory irritation, trigeminal nerve receptors are stimulated and, with penetration into the main airways, vagal nerve receptors may also be involved. Effects are concentration-dependent and range from mild discomfort all the way to severe pain [30], [31]. Depending upon the irritant and the susceptibility of the individual, neural reflex responses can include lachrymation and blinking of the eyes, pain in the eyes, nose and throat, chest tightness, coughing, breath-holding, laryngeal spasms, bronchoconstriction and dyspnea (inability to breathe).

Bronchoconstriction and dyspnea may be key factors affecting occupants' behaviour, often resulting in escape being aborted or not even attempted. The medical physiology literature is replete with references to bronchoconstriction being a reflex response to inhalation of irritants [32], [33], [34]. Dyspnea refers to an individual's subjective feeling of the inability to breathe rapidly and deeply enough to satisfy respiratory demands [32]. This condition may then induce secondary physiological and behavioural responses [35], such as those described in A.2, that can have an immediate detrimental effect on tenability; see also A.5. Depending on the nature of induced behavioural responses, exposure to upper-respiratory tract sensory irritants can immediately compromise tenability.

Assessment of neural reflexes has seldom been practical and integrative mechanisms of such responses have rarely been studied in experimental animals and not at all with humans [36]. The mouse RD_{50} 1) has been proposed as being associated with intolerable irritancy in humans [37], but it is unclear as to the relationship of such data on sensory irritation in mice to compromised tenability of humans. The mouse is an obligatory nose-breather, with the nose being the most sensitive reflexogenic zone in most animals. In addition, the breathing frequency of the mouse is 15 times higher than for humans. As a result, humans would be expected to be somewhat less sensitive. This has been supported by experimental human exposure to non-flaming combustion of red oak in which the RD_{50} concentration of its fire effluent resulted in effects that were reported to be quite irritating, but tolerable for 3 minutes [38]. However, exposure to three times the RD_{50} concentration of red oak fire effluent was described as being highly irritating and probably not easily tolerated for the 3 minutes [38]. Thus, at least for red oak fire effluent, there would appear to be a factor of about three between the mouse RD_{50} concentration and that causing rapid, intolerable irritation for humans.

Three times the mouse RD_{50} concentration for hydrogen chloride (ca. 300 $\mu l \cdot l^{-1}$) results in an estimated highly irritating level for humans to be about 1 000 $\mu l \cdot l^{-1}$. Furthermore, analysis of time-response relationships for respiratory rate depression in mice [39] supports the concept that instant effects of exposure to hydrogen chloride may occur at concentrations equal to or exceeding about 1 000 $\mu l \cdot l^{-1}$. Consistent with experimental data, this International Standard assigns a value of 1 000 $\mu l \cdot l^{-1}$ for instantaneous sensory irritant effects from exposure of humans to hydrogen chloride (see 6.2.1). This value is equated to the FEC = 1 criterion, corresponding to the median value of a log-normal distribution of responses, with one-half of the population being more susceptible and one-half being less susceptible.

1) The RD_{50} is that concentration of an irritant toxicant statistically determined to depress the respiratory rate of exposed mice by 50 %.

This categorical approach appears to be justified for emergency response situations where exposure profiles are uncontrolled and difficult to quantify. Subsequent allowances are then made for susceptible subpopulations (see A.5.2). Other halogen acid irritants, i.e., hydrogen bromide and hydrogen fluoride, were assessed in a manner comparable to that for hydrogen chloride. Criteria for other irritants were derived from analysis of relevant data cited in References [5] to [13].

NOTE Studies using healthy, young adult baboons under controlled experimental conditions have demonstrated failure to cause their inability to perform a conditioned escape paradigm following exposure to hydrogen chloride and acrolein at any concentration up to those that caused post-exposure lethality due to lung irritation[3] (see A.4.3). In spite of these findings, more conservative criteria were chosen for use in this International Standard (see 6.2.1).

Rationale was based, in part, on recommendations of the AEGL Advisory Committee. Although the baboon study demonstrated their uncompromised ability to perform a conditioned escape paradigm following exposure to considerably higher concentrations of hydrogen chloride, other studies cited by the AEGL Committee implied potentially serious health effects at concentrations in excess of 500 μl·l-1 for 15 minutes [40]. Following review of all of the baboon exposure studies, the AEGL Committee concluded that they resulted in effects consistent with exposure criteria associated with AEGL-2 [41].

For the purposes of this International Standard, it was further felt that the experimental paradigm used in the baboon escape studies was not sufficiently relevant to the compromised tenability of humans in typical fire scenarios so as to enable valid extrapolation. The baboon studies used subjects that were extremely well trained to accomplish a relatively simple task within a confined, familiar environment. In contrast, people involved in unwanted fires can generally be expected to perform relatively complex actions within a much larger occupancy with which they are not very familiar, along with little or no escape training or presence of evacuation management. The consequences of these differences may be more behavioural than physiological (see A.2.2 and A.2.3). However they tend to diminish the significance of the baboon escape studies as they might apply to compromised human tenability. On the other hand, the baboon studies do suggest that subjects well trained to carry out a specific task may still be capable of performing that task in the presence of sensory irritant concentrations normally considered as tenability-compromising.

A.4.2.3 Dose-dependent pathological effects

Although dose-dependent pathological effects due to upper respiratory irritants can occur, there is currently no model that can adequately address such effects within the context of exposure to rapidly changing fire effluent atmospheres. Since these effects are related to both concentration and time of exposure, they take longer to be manifest than those caused by concentration-related sensory effects and would not be expected to have a direct impact on tenability during a fire.

A.4.3 Pulmonary irritation

Depending on the concentration of the irritants and water solubility, the scrubbing ability of moist oral and nasal mucosa can be exceeded, with deep lung penetration then causing effects that are related both to the concentration and to the duration of exposure (i.e. dose). Irritants may also be carried deep into the lungs by aerosols and particulates.

Although generally not regarded as presenting a threat to tenability during a fire, pulmonary irritation can cause post-exposure respiratory distress and even death from a few hours up to several days after exposure due to pulmonary oedema.

A.5 Susceptibility of subpopulations

A.5.1 General

Essentially all toxicological data relative to gaseous fire effluents have been derived from laboratory experiments using young, healthy animal surrogates. However, the overall human population contains a number of subpopulations that can exhibit greater susceptibility to fire-effluent toxicants. The largest such subpopulations are the very young, the elderly and approximately 15 % of children and about 5 % of adults who are asthmatics.

Infants and young children are particularly susceptible to asphyxiant toxicants due to a greater volume of air inhaled per minute relative to their body mass. The elderly, particularly those with compromised cardiovascular systems, are also especially susceptible to asphyxiant toxicants; see also A.3. Asthmatics, along with sufferers of other lung conditions such as chronic obstructive pulmonary disease (COPD), including chronic bronchitis and emphysema, are particularly susceptible to bronchoconstriction upon even brief exposure to low concentrations of irritants.

A.5.2 Accommodating susceptible subpopulations

In this International Standard, FED and/or FEC values of 1,0 correspond, by definition, to the median value of a log-normal distribution of responses, with one-half of the population being less susceptible and one-half being more susceptible [2)]. Such a concept is commonly used for dealing with response distributions because confidence limits are narrowest at the midpoint of the response curve [42]. This means that, statistically, 50% of the population would be expected to experience tenable conditions, with 50% then expected to experience compromised tenability.

Users of this International Standard have the flexibility to choose other FED and/or FEC threshold criteria as may be appropriate for fire safety objectives that are intended to reduce the percentage of the population that would statistically be estimated to experience compromised tenability.

For example, based on the assumption of a log-normal distribution, FED and/or FEC threshold criteria of 0,3 translate to 11,4% of the population being susceptible and, therefore, statistically estimated to experience compromised tenability [43]. Even lower threshold criteria could be employed, with 0,2 FED/FEC translating to 5,4% and 0,1 FED/FEC translating to 1,1 % of the population. However, there is no threshold criterion so low as to be statistically safe for every exposed occupant. It is also important to recognize that these percentages for compromised tenability are statistically derived values that only demonstrate the trend resulting from reducing FED/FEC threshold criteria. There is no assurance that the absolute percentages are valid.

Whatever the rationale used for choosing FED and FEC threshold criteria, it is necessary to use a single value for both FED and FEC in a given estimation of the time to compromised tenability.

A.6 Interactions of toxicological insults

The components of life threat are treated in this International Standard as acting independently. In practice, however, some interactions between the components are known to occur. For example, the effects of sensory irritants on the eyes are additive with smoke obscuration, resulting in additional disorientation and, hence, detrimental effects at lower levels of smoke optical density than would be the case in the absence of irritants. Irritants can also have some influence on asphyxiation. They can affect breathing patterns, causing broncho-constriction and alteration of lung ventilation/perfusion ratios. These effects can impair gas exchange in the lungs, resulting in further asphyxiant effects that can be considered potentially additive with the direct effects of inhaled asphyxiant gases. On the other hand, effects of irritants on respiration can also reduce the rate of uptake of inhaled asphyxiant gases. Overall, these interactions are considered to be secondary in comparison to the primary effects of the individual components.

2) A log-normal distribution for human responses to fire gas toxicants is an *a priori* assumption, but in the absence of experimental data, this premise is more defensible than any other that can be made.

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