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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



DRAFT International Standard

ISO/DIS 13571-1

Life-threatening components of fire —

Part 1: Guidelines for the estimation of time to compromised tenability and escape capability from exposure to smoke toxicants — Method A

ICS: 13.220.01

ISO/TC 92/SC 3

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13571-1 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 3, *Fire threat to people and environment*.

This first edition cancels and replaces the second edition (ISO 13571 :2012), which has been technically revised.

The main changes are as follows:

- Additional expressions for enabling calculation of asphyxiant tenability over a range of activity levels from at rest to heavy work.
- Guidance on estimation of asphyxiant and irritant tenability threshold (Point of Departure) levels have been revised and further developed.
- Informative guidance on estimation of post-exposure health effects has been included.
- Further information has been included to extend and clarify the basis of the derivation of threshold levels and application to different occupant populations, including children, the elderly and those with health conditions.

Introduction

ISO 13571 series is a set of standards developed for estimation of time to compromised tenability and escape capability for occupants when exposed to a fire environment. Different threats are evaluated separately for exposure to acute toxicants, heat and smoke. The time to compromised tenability is the shortest of the determined times to compromised tenability for each individual threat.

ISO 13571 series is composed of 5 parts:

- ISO 13571-1 describes a model for smoke toxicity assessment of time to compromised tenability and escape capability of 50 % of an exposed occupant population, and threshold tenability limits for the sensitive members of an exposed population including children, elderly and health compromised.
- ISO/TR 13571-2 (Technical report) describes examples of application of ISO 13571 series [TO BE REVISED].
- ISO 13571-3 describes a model for smoke toxicity assessment of time to compromised tenability based on lethality endpoints for an exposed occupant population (excluding hypersensitive).
- ISO/TR 13571-4 (Technical report) gives examples of comparisons between parts 1 and 3 in different fire scenarios.
- ISO 13571-5 describes models for heat exposure, smoke exposure, and a simplified model for toxicity assessment based on mass loss of combustible.

Chronic or environmental exposure are not covered in ISO 13571 series.

This document is intended for estimation of time to compromised tenability and escape capability for occupants when exposed to a fire environment for applications where the time-concentration curves for fire scenarios are available (for example from fire dynamics modelling or large-scale fire experiments). The standard may be used for hazard calculations and modelling as applied to Available Safe Escape time (ASET) and Required Safe Escape time (RSET) calculations and models.

The document provides expressions for calculation of time and exposure doses to tenability endpoints for 50 % of an exposed occupant population and for estimation of threshold limits designed to protect essentially all occupants. This includes mixed general populations with children, the elderly and adults with health conditions in all occupancies including buildings and transport systems.

The calculation expressions in this document have been derived as far as possible from human behavioural and physiological tenability data obtained from experimental and accidental exposures, especially data from exposures during fire incidents, data from experiments on non-human primates, and experiments involving rodents (rats and mice). The expressions and endpoints derived from these data have been developed to provide assessment methods most relevant to the tenability and particularly the escape capability of human occupants of building or transport fire scenarios.

The main areas of revision in this edition from ISO 13571:2012 are as follows:

- For this third edition the main expressions for calculation of tenability endpoints for active walking adults have been retained, as in the second edition, but additional expressions have been provided for which the volume of air breathed each minute (V_E) has been separated out as user defined term. This provides more versatility to enable the user to calculate tenability times for occupants over a range of activity levels including at rest, moderate activity (such as rapid walking to evacuate) or heavy work (such as running along a tunnel). This also incorporates the stimulatory effect of inhaled high CO_2 concentrations, enabling V_E to be calculated throughout the physiological range (~8-70 l/min) and the resulting effects on the uptake and time to compromised tenability from asphyxiants. Expressions for the asphyxiant effects and time to compromised tenability for decreased oxygen concentrations and.
- For the narcotic effects of inhaled CO_2 at high concentrations (which were referenced in the second edition) have now been included in this edition.
- For this edition, although the main endpoints for asphyxiant and irritant tenability are the same as for the previous edition the guidance on estimation of threshold, Point of Departure (POD), levels have

been revised and further developed. For asphyxiants tenability is compromised by confusion and loss of consciousness after inhalation of a sufficient exposure dose. For smoke irritants, tenability depends on exposure concentration and is compromised by eye and respiratory tract pain, visual and breathing difficulties sufficient to result in a high probability of escaping occupants turning back or being unable to continue through irritant smoke.

- As with the previous edition the main intended application of this standard is the calculation to times of compromised tenability during exposure at a fire incident, for application to time up to which occupants are able to escape or shelter without compromised tenability. For this reason, the main application does not include consideration of potential post-exposure adverse health effects in fire survivors. In general, it is considered that such effects should be minimal providing the limits for compromised tenability during the incident are not exceeded. In order to enable consideration of such potential post-exposure hazards in survivors when appropriate (for example when threshold limits may be exceeded), guidance has been included in an informative [Annex C](#) in this edition for estimation of threshold level for asphyxiant exposures above which there may be significant risk of post-exposure neurological or cardiovascular health effects and expressions for calculation of threshold exposure doses of irritant gases and particulates for risk of inhalation injury from lung inflammation.
- Further information has been included, mainly in the Appendices, to extend and clarify the basis of the derivation of the calculation expressions and endpoints, the derivation of threshold levels and application to different occupant populations. The guidance in this standard draws on that derived independently for the AEGL (*National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances*), [\[6\]](#) [\[7\]](#) [\[25\]](#) [\[26\]](#) [\[27\]](#) [\[28\]](#) [\[29\]](#) [\[30\]](#) [\[31\]](#) and comparisons are presented in ISO/TR 13571-4.

The guidance in this International Standard (ISO 13571-1) 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.

Estimation of occupants' tenability when exposed to a fire environment ultimately involves their ability to perform behavioural, 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 can depend upon each occupant's location and movement, along with numerous other characteristics specific to the occupant. 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 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 (ISO 13571-1) 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 formulae are to be used as input to a fire hazard or risk analysis. 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.

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.

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 —

Part 1:

Guidelines for the estimation of time to compromised tenability and escape capability from exposure to smoke toxicants — Method A

1 Scope

This International Standard (ISO 13571-1) is one of many tools available for use in fire safety engineering. It is intended to be used in conjunction with fire test data such as those detailed in ISO 13571-5 and 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 [B.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.

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 formulae 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.

The life-threatening components addressed in the 13571 series include fire-effluent toxicity, heat, and visual obscuration due to smoke. In cases where the effluent composition is available, the toxic gas model is 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 in ISO 13571-5.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 19701, *Methods for sampling and analysis of fire effluents*

ISO 19702, *Sampling and analysis of toxic gases and vapours in fire effluents using Fourier Transform Infrared (FTIR) spectroscopy*

ISO 13943, *Fire safety — Vocabulary*

ISO/TR 16738, *Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 tenability

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

Note 1 to entry: 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.

3.2 adjustment factor

factor for the incorporation of quantitative data on interspecies differences or on human variability in either toxico-kinetics (variability in inhaled dose and metabolism) or toxico-dynamics (mode of action causing the critical effect) into the risk assessment procedure

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 sensory, 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 formulae 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 a log-normal or probit 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](#)). Threshold levels estimated to affect tenability for approximately 1 % of an exposed population are derived from Point of Departure (POD) animal toxicity data and reported findings from human exposure data [\[2\]\[6\]\[9\]\[25\]\[26\]\[27\]\[28\]\[29\]\[30\]\[31\]](#).

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 resulting in lung injury are manifested from a few hours up to several days after

exposure and are not normally expected to have a direct impact on tenability during exposure at a fire scene (see [A.4.3](#)).

Providing asphyxiant and irritancy thresholds are not exceeded during exposure then significant post-exposure lung injury from irritants and significant post-exposure neurological or cardiovascular injury from asphyxiants are considered unlikely to occur. Additional guidance on threshold exposure doses that may result in post-exposure injury is given (see [A.4](#)).

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, whereby the accumulated exposure dose is expressed as a fraction of the exposure dose required to cause compromised tenability. 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.

4.2.4 Relevant assumptions and exclusions are as follows:

- 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) Exposed occupants are considered to be at relatively normal ambient environmental conditions and at altitudes below which reduced ambient oxygen could be a factor, and performing at a moderate level of physical activity. Deviation from these conditions can affect susceptibility.
- c) Any interactions between aerosols, particulates and 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 and particulate effluents.
- d) Adverse health effects subsequent to exposure to fire atmospheres are not considered in relation to tenability during exposure, although it is recognized that post-exposure effects occur where tenability limits during exposure are exceeded. 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 with respect to tenability during exposure at a fire scene. Additional guidance has been provided on post exposure adverse health effects from inhaled doses of asphyxiants with risk of post-exposure cardiovascular and neurological effects and to inhaled doses of lung irritants associated with a risk of lung injury.
- e) 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 or show a high probability of turning back rather than enter or continue through smoke places a limitation on the time during which escape may be attempted and is considered.

The formulae 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. If the estimated time is 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 fire conditions specified in terms of time-concentration profiles for toxic gases and smoke particulates. 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 or final exit is the outcome to be considered, the time to compromised tenability can reasonably be equated to the available safe escape time (ASET).

The method has been developed specifically to address issues relating to exposure of occupants to developing fires.

The main purpose of the expressions is to enable calculation of time to compromised tenability during exposure to fire scenarios. The particular endpoint addressed is the time at which a significant proportion of an exposed population becomes incapacitated to the extent that they are unable to make a safe escape. The expressions are also protective against significant post exposure injury and death providing the endpoints for compromised tenability are not exceeded.

During fire incidents enclosure occupants (occupants of buildings and transport systems) are typically exposed to one of three types of exposure scenario^{[1][2]}:

1. Occupants in the same enclosure as a fire exposed to smoke particulates, irritants and asphyxiant gases (and or heat) starting from low concentrations then increasing rapidly over a period of a few minutes to incapacitating concentrations.
2. Occupants leaving a relatively clear enclosure to enter a smoke-filled escape route containing concentrations varying from low levels to those capable of causing incapacitation within a short period (a few minutes, a few seconds or even after a single breath). Occupants are in such cases exposed to a near square wave effluent concentration profile.
3. Occupants trapped in an enclosure (or remaining in a designated refuge) which is initially clear but gradually fills with smoke and toxic gases by infiltration over an extended period of up to (but rarely exceeding) an hour.

In these scenarios occupants are exposed to and affected by a sequence of hazards, typically beginning with the immediate effects of exposure to irritant smoke, then followed by effects of exposure to asphyxiant gases and/or heat. Key aspects of these exposure scenarios in relation to the development of tenability expressions are that they generally involve short exposure periods of a few minutes, and that conditions can change very rapidly, so that the expressions need to be able to address effects of high exposure concentrations and short tenability times. An advantage when estimating tenability times in such situations is that due the exponential increase in gas concentrations at a certain time during most fires, calculated times to incapacitation may show only small changes when model parameters are varied.

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 Fractional Effective Dose (FED) ^[3] and Fractional effective concentration (FEC) ^[4] 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 may 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. While a threshold level of 0,3 FED or FEC is recommended, further 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 thresholds 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.3](#) and [A.4](#)). Although the primary purpose of this standard is estimation of compromised tenability during exposure at a fire incident, guidance is given on the risk of significant post-exposure health effects. Providing the compromised tenability limits in this standard are not exceeded during the period of exposure, post-exposure health effects are likely to be minor. 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 formulae presented in this International Standard.

5.7 The methodology described for toxic gas exposures can be validated only to a limited extent from human data. It is necessary to recognize that uncertainty exists in the precision of the experimental data upon which the formulas 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 formulas 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 fractional effective dose 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 [Formula \(1\)](#):

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

where

- C_i is the average concentration, expressed in $\mu\text{l} \cdot \text{l}^{-1}$, 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 $\mu\text{l} \cdot \text{l}^{-1}$;
- t Is the exposure period expressed in minutes.

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 [Formula \(1\)](#) reduces to:

$$X_{\text{FED}} = \sum_{i=1}^n \sum_{t_1}^{t_2} \frac{1}{t_i} \cdot \Delta t \quad (2)$$

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 asphyxiant gases the dose inhaled depends on three main variables:

- Exposure concentration C
- Volume of air breathed per minute (V_E) in relation to body size
- Exposure time Δt

The main case used for the asphyxiant expressions is for an adult human engaged in moderate physical work such as rapid walking horizontally or down stairs during an evacuation, with a V_E under ambient conditions of 20 litres/minute. In [Annex B](#), general case versions of the asphyxiant expressions are presented in which V_E is included as a variable to enable uptake calculations for resting and heavy work conditions (such as running). In all mammals V_E for a given activity level varies as a function of body surface area to mass ratio so that the rate of dose uptake is greater for smaller humans or animals.^{[2][5]} To the extent that the following asphyxiant expressions are derived from animal studies (such as primates or rodents) the effects of body size on uptake is taken into account. Some inhaled fire gases, especially CO_2 , further increase V_E by stimulating breathing. This effect is also included in the uptake expressions.

The main asphyxiant gases occurring in fire effluents are CO and HCN, which cause hypoxic asphyxia by impairing the carriage of oxygen in the blood and its delivery to and use in body tissues, especially brain and heart, resulting in incapacitation due to collapse and loss of consciousness.^{[1][2]} The effects of CO and HCN are considered to be additive on a fractional dose basis. Decreased oxygen concentration in fire effluents is also a potential additive contributor to hypoxia, but is considered unlikely to make a significant contribution at inhaled concentrations above 13 % oxygen. Inhaled nitrogen oxides can also contribute to hypoxia due to methaemoglobin formation, decreasing the carriage of blood oxygen, but concentrations occurring in mixed fuel fires are too low for NOx to make a significant contribution to hypoxia. Methaemoglobin also detoxifies

inhaled cyanide somewhat due to the formation of cyanomethaemoglobin.^[6] The main contribution of carbon dioxide to developing asphyxia is that it stimulates respiration and thereby increases the rate of uptake of CO and HCN.^{[1][2]} High inhaled concentrations of CO₂ above 5 % also cause incapacitation due to dose-dependent respiratory distress and narcosis. This narcosis does not result from hypoxia so is treated as a separate potential cause of incapacitation. During compartment fires, incapacitation due to effects of asphyxiant gases is generally predicted before the narcotic effects of CO₂ are likely to be significant. On this basis the main asphyxiant model considers the effects of CO and HCN in conjunction with effects on V_E depending on physical activity level of exposed subjects and inhaled CO₂ concentrations. An expression for the calculation of asphyxiant FED from oxygen depletion ([Formula 8](#)) is also presented for use as an additive term with the FEDs for CO and HCN where necessary, and an expression for the calculation to FED for narcosis from CO₂ for use as a separate term with situations of exposure to high concentrations of CO₂ in the absence of significant concentrations of asphyxiant gases.

6.1.2 Allowance for activity and ventilation levels for asphyxiant uptake models

For any given exposure concentration the uptake rates of asphyxiant gases are directly proportional to an occupant's activity level expressed in terms of volume of air breathed each minute (V_E). This varies between approximately 6 l/min for sleeping adults to maximum levels of up to approximately 100 l/min for maximal exercise in air. The main case considered for this standard is for occupants engaged in moderate activity involving rapid horizontal walking or walking down stairs in order to escape from an occupancy at a V_E of 20 l/min. The asphyxiant expressions in the following sections are designed for this specified case. For application to a full range of scenarios including occupants at rest ($V_E \sim 8,5$ l/min), in moderate activity ($V_E \sim 20$ l/min) or engaged in heavy work such as running on the level or climbing up stairs ($V_E \sim 40$ l/min) a general case set of expressions is presented in [Annex B](#), for which V_E is included as a variable. This may be useful for the evaluation of cumulative uptake and tenability in scenarios such as for occupants exposed for a period while sheltering at rest, then engaged in moderate or heavy activity while walking or running to escape. Both the main and general case models include expressions to calculate the further increases in V_E from different activity levels in air due to the hyperventilatory effect of increased inhaled carbon dioxide concentrations.

6.1.3 Adjustment factors for asphyxiant models

The asphyxiant models provide an estimate of the exposure dose predicted to cause compromised tenability for 50 % of an exposed mixed human population (ICt_{50}) including an estimate of the Point of Departure (POD) (exposure threshold with 1 % incidence) for more sensitive subjects including children, the elderly and those with health impairments.

Estimates for these parameters had been derived using human experimental or incident data to the extent available, combined with measured incapacitation data from animal experiments, mainly using non-human primates and also rats. Where human data have been obtained from subjects with a limited range of characteristics (for example adults rather than children), or under differing activity conditions (for example at rest rather than walking) then it is necessary to apply adjustment factors to allow for these variations.

Where data are obtained using animal models it is necessary to consider inter-species differences in toxic sensitivity, representing differences between the inhaled dose resulting in incapacitation between humans and animals, and to apply compensatory adjustment factors (AF) where appropriate. Where 1% POD threshold levels are estimated from animal data it is also necessary to consider implications for the measured sensitivity distribution in the animal model compared to that likely in the human population.

The starting point for the toxicity models for each gas is the measured incapacitation dose distribution (counted during exposure) for groups of animals under laboratory conditions. The main advantage of this method, especially is that measurements can be made under controlled conditions using relatively large numbers of animals, providing data within relatively narrow ranges of statistical uncertainty for the 50 % incidence of incapacitation for different specific exposure time periods (ICt_{50} exposure doses). From the probit analysis of the data the ICt_{01} exposure dose can also be calculated, although the range of uncertainty is considerably greater than for the ICt_{50} . A limitation relating data from rodents to humans is the greater diversity and range of sensitivity in mixed human populations. For example the 1 % incidence POD for rats is calculated statistically from the experimental data from a narrow sensitivity distribution in young, healthy, rats of a specific strain.^[1] For restrained rats the compromised tenability endpoint was measured as failure

of hind limb shock withdrawal reflex.^[1] For active rats exercising in a wheel compromised tenability was identified as the time when failure to walk followed by tumbling occurred.^[1] The sensitivity distribution in a diverse human population including individuals with greater genetic variation, greater age range (including children and older individuals) is therefore greater than that in laboratory rats. Primate experiments were conducted on genetically diverse, but all healthy young adult animals^[1].

Adjustment parameters considered appropriate for different conditions are presented for the individual asphyxiant gas models and discussed in [A.3.6](#).

6.1.4 Asphyxiant model for carbon monoxide

There are two methods for measuring and expressing the dose of CO resulting in incapacitation of an exposed human or animal subject. One method is in terms of the Cⁿt exposure dose. This is a nominal dose representing the dose available for inhalation in terms of exposure concentration and exposure time, rather than the dose actually inhaled, which further depends on a range of other parameters including body size, respiration ventilation and the level of blood saturation. The other method is to measure (or calculate) the blood percentage carboxyhaemoglobin (%COHb), which provides an accurate measure of the dose of CO actually inhaled and retained, and is therefore much more accurate than the exposure dose method ^[2] ([A.3.3](#)). The first method uses simple exposure concentration and time data. The second method enables uptake endpoints to be calculated or measured and compared with human and animal data for the relationship between %COHb and signs of incapacitation.

This has shown a very good relationship between %COHb level and the severity of signs of incapacitation at the time of exposure during acute CO exposures. It also has the advantage of enabling comparison with the large published data sets on %COHb levels in humans injured and dying from CO exposure. The relationships between CO exposure dose, %COHb, incidence and extent of incapacitation and death have been reviewed in Purser, Purser and Mcallister and in the AEGL report with respect to derivation of exposure limits for escape impairment and lethality in humans.^{[1][2][7]} Studies of acute accidental human exposures to CO, including fire exposure show a good relationship between %COHb at the time of exposure and severity of incapacitation or incidence of deaths ^{[8][9]}.

The exposure dose of CO predicted to cause incapacitation uses a simple constant Cⁿt exposure dose value of 35,000 µl.l⁻¹ minutes. This was from obtained from experiments on juvenile baboons subjected to an escape paradigm.^{[10][11][12]} Using the Coburn Forster Kane ^{[13][14]} and experimental human data, a dose of 35,000 µl/l.min produces approximately 30 % blood carboxyhaemoglobin saturation in humans having average adult body weight and a respiratory minute volume of 20 l/min. Active cynomolgus monkeys performing a behavioural paradigm were found to collapse unconscious at 30 % COHb for an exposure dose of 27,000 µl/l.ppm.min while resting monkeys collapsed unconscious at 40 % COHb ^{[9][15]} for an exposure dose of ~47,000 µl/l.min. Based on this and reports from human exposures, this exposure dose is considered predictive of a 50 % incidence of incapacitation in exposed adult humans engaged in light exercise such as rapid walking horizontally or down stairs while escaping a fire. Although rat incapacitation and lethality data are available for CO derivation of an expression from the human and other primate data was considered more reliable due to the considerable uncertainties in extrapolating between rats and humans, including inter-species sensitivity differences, between rat lethality incapacitation thresholds, with published ranges of 4,3-7 ^{[35][51]} and large differences in body size and respiratory parameters.

For the main case in this standard for an adult human engaged in moderate activity (respiratory minute volume [VE] 20 l/min, rapid walking to escape) time to incapacitation by inhalation of CO is given by: