

Code of practice for

Assessment of hazard to life and health from fire —

**Part 2: Guidance on methods for the
quantification of hazards to life and
health and estimation of time to
incapacitation and death in fires**

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Foreword

This part of BS 7899 has been prepared by Technical Committee FSH/16.

It has been developed from DD 180:1989 *Guide for the assessment of toxic hazards in fire in buildings and transport*.

This part of BS 7899, together with parts 1 and 3, supersedes DD 180, which will be withdrawn when BS 7899-3 is published.

The major hazards to life and health from fires are exposure to toxic fire effluents and heat. Exposure to these hazards, together with visual obscuration by smoke, also affect the ability of people to escape from fires.

Existing prescriptive safety regulations and codes contribute to the control of life threat in fires, but despite their influence there was an increasing incidence of death and injury from fires during the 1960s, 1970s and 1980s, particularly in relation to death and injury resulting from exposure to toxic smoke.

In addition to the current unacceptable incidence of death and injury from fire, a further problem is that the existing prescriptive control methods such as those given in the Building Regulations are inadequate for control of modern systems, as well as providing a potential restriction on useful novel developments. There is therefore a great need for the development of effective methods for the assessment of life threat in fire and its regulation, based upon sound fire safety engineering principles.

Major advances have been made in recent years in the development of fire engineering tests and calculation methods for the prediction of fire behaviour, and for the prediction of hazards to life and health from exposure to fire effluents. A basis now exists for making evaluations of the hazards to life in fires, and BSI is currently participating in work on the development of test and evaluation methods being developed in the UK, in the EU generally and in the International Organization for Standardization (ISO).

This methodology is not yet completely available, but questions of hazards to life and health from fires still have to be faced. BS 7899 provides the best advice currently available for the assessment of hazard to life and health from fires, although further developments are expected in the future.

In order to provide guidance on how these processes can be assessed, BS 7899 is written in a number of parts.

Part 1 — General guidance.

Part 1 provides an outline guide to the factors which should be considered when assessing the hazards to life and health presented by fires in structures (e.g buildings and transport).

.At appropriate points it calls up documents in the series, which provide specific practical guidance on how the various elements of the hazard assessment can be performed.

Part 2 — Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires.

This part of BS 7899 provides detailed guidance on methods for the quantification of hazards to life and health and for the estimation of time to incapacitation and death in fires. It also includes methods for the estimation of lethal toxic potency from a chemical analysis of small-scale thermal decomposition test atmospheres.

Part 3 — Worked examples illustrating hazard assessments of various types.

This part is in preparation.

Other documents may be added in future to cover different aspects of the subject.

It has been assumed in the preparation of this standard that the execution of its provisions will be entrusted to appropriately experienced or informed people for whose guidance it has been prepared.

Annex A is informative.

As a code of practice, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 26, an inside back cover and a back cover.

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Introduction

BS 7899 has been designed to provide a code of practice to be followed when assessing hazards to life and health for potential fire scenarios.

Part 1 of this code of practice (BS 7899-1) describes the many factors that can influence the threat to life and health from fires. It recommends a stepwise approach to a hazard assessment, by means of which the various factors can be considered. A key step in this process (step 4) is the quantification of hazardous effects from a fire and the estimation of time to incapacitation and death. This step takes as input the time-concentration or time-intensity curves of the life threatening components of fire effluent at the breathing zone of an exposed person and performs calculations to enable estimates to be made of the hazardous effects at different times during an exposure.

This part of BS 7899 contains calculation methods which can be used for estimating the effects of exposure to the major hazardous components of fire effluent:

- a) asphyxiant and irritant gases;
- b) smoke (obscuration);
- c) convected and radiant heat.

The methods described in this part of BS 7899 are designed to be applied to a variety of fire scenarios using a variety of types of input data. A relatively simple scenario might involve an assessment of the developing hazard arising from the slow thermal decomposition of a small object made of a single material in a closed room, using input data obtained from a full scale test. A more complex scenario might involve an assessment of potential hazards to life from a range of possible fires at the design stage of a large multi-compartment building. In order to complete this assessment, a wide range of factors would need to be considered and a variety of fire engineering calculations would be necessary, all of which are beyond the scope of this part of BS 7899. However, at some point in such an analysis, consideration would have to be given to the effects on people of exposure to estimated fire effluents. The methods presented in this part of BS 7899 are intended to be directly applicable to such an estimation.

A number of different methods can be used for the estimation of toxic hazards from fires and several different approaches are described in this part of BS 7899. The methods described include:

- the application of time-concentration curves for individual toxic gases, obtained from large-scale fire tests or from fire modelling, for estimation of time to incapacitation or death using physiological calculation methods for humans;
- the application of toxic potency data derived from small-scale combustion toxicity tests to toxic hazard assessment for full scale fires;
- the estimation of lethal toxic potency from a chemical analysis of small-scale combustion toxicity test atmospheres (for use in method 2).

1 Scope

This part of BS 7899 provides guidance for fire safety practitioners on methods for the quantification of hazards to life and health. It includes methods for the calculation of fire effluent toxicity, smoke obscuration and thermal components of fire hazard analysis for estimation of time to incapacitation and death in fire. Also included are methods for the estimation of lethal toxic potency from a chemical analysis of small-scale combustion toxicity test atmospheres and for the application of such data to toxic hazard assessments for fires.

2 Terms and definitions

For the purposes of this part of BS 7899 the following terms and definitions apply.

2.1

approximate lethal dose (ALD)

estimate of the LCt_{50}

2.2

asphyxiant

substance which may cause loss of consciousness or death by depriving the brain tissues of oxygen

2.3

combustion toxicity

capacity of a substance within an effluent to cause injury to a living organism

NOTE This definition is based on an ISO Guide 52 definition and PD 6503-1.

2.4

escape impairment

effect of exposure to fire effluent and/or heat whereby escape capability is significantly reduced

NOTE This may be due to fire effluent or heat inhibiting occupants from entering affected areas or by reducing the efficiency or speed of escape in affected areas.

2.5

exposure dose

potential dose of a toxicant available by inhalation expressed as the exposure concentration multiplied by the exposure time

2.6

fire effluent

total gaseous, volatile and particulate (liquid or solid) products from combustion or pyrolysis

2.7

fire hazard

physical situation with a potential for harm to life or limb, or damage to property, or both, from the effect of fire (see BS 6336)

2.8

fire scenario

generalized description of an actual or hypothetical fire incident

2.9**fractional effective concentration (of smoke) (FEC)**

concentration of smoke present in a fire at any time divided by the concentration considered to significantly affect escape efficiency

2.10**fractional effective dose (FED)**

average exposure dose of one or more toxic effluents present in a fire over a defined period of time divided by the exposure dose required to obtain a defined toxic endpoint (escape impairment, incapacitation or death)

2.11**fractional irritant concentration (FIC)**

concentration of one or more irritant effluents present in a fire at any time divided by the exposure concentration required to obtain a defined toxic endpoint (escape impairment, incapacitation or death)

2.12**fractional lethal dose (FLD)**

average exposure dose of one or more toxic effluents present in a fire over a defined period of time divided by the lethal exposure dose

2.13**irritant**

substance which can cause discomfort, pain or tissue damage to the mucous membranes of the eyes, nose, throat and lungs, which can lead to a degree of incapacitation or death

2.14**LC₅₀ (lethal concentration, 50 %)**

concentration of a toxic gas or fire effluent statistically calculated to cause the deaths of 50 % of test animals exposed for a specified time

NOTE 1 The LC₅₀ is expressed as ppm for a toxic gas and in g·m⁻³ for a fire effluent.

NOTE 2 When comparing LC₅₀ data, both the exposure duration and the post-exposure period over which the deaths were scored need to be taken into account.

2.15**LCt₅₀ (lethal exposure dose)**

product of LC₅₀ and the exposure duration over which it was determined

NOTE The LCt₅₀ is expressed as ppm·min for a toxic gas and in g·m⁻³·min for a fire effluent.

2.16**hazard to life and health**

consequences (injury or loss of life) to be expected from the effects of exposure to toxic effluent and heat in fires, with respect to their nature, quantity and rate of production and concentration (see PD 6503-1)

2.17**risk to life and health**

expected extent of injury or loss of life from a fire, defined in terms of probability as the product of:

- frequency of occurrence of an undesired event to be expected in a given technical operation or state; and
- hazard to life and health

2.18**mass charge**

mass of material exposed to burning conditions

2.19**mass charge concentration**

concentration of fire effluents from a material defined in terms of the mass of material exposed to burning conditions (mass charge) and the volume into which the effluent is dispersed (g·m⁻³)

2.20**mass loss**

mass of material consumed by or otherwise lost during burning

2.21**mass loss concentration**

concentration of fire effluents from a material defined in terms of the mass of material decomposed (mass loss) and the volume into which the effluent is dispersed, expressed in g·m⁻³

2.22**mass loss exposure dose**

mass loss concentration multiplied by the exposure time expressed in g·m⁻³·min

2.23**pyrolysis**

thermal decomposition of materials in the absence of flaming

NOTE In the context of this standard the term pyrolysis is restricted to thermal decomposition in the absence of oxygen.

2.24**respiratory depression 50 % (RD₅₀)**

statistically calculated concentration of a sensory irritant required to reduce the breathing rate of laboratory rodents (usually mice) by 50 %

2.25**toxic hazard**

consequences (injury or loss of life) to be expected from the effects of exposure to toxic effluent in fires, with respect to their nature, quantity and rate of production and concentration (see PD 6503-1)

2.26

toxic potency

amount (exposure dose) of a toxic fire effluent required to elicit a specific toxic effect

NOTE 1 Toxic potency may be expressed in terms of individual products [for example the lethal exposure dose of carbon monoxide ($\text{ppm}\cdot\text{min}$ or $\text{g}\cdot\text{m}^{-3}\cdot\text{min}$) or the mixed effluents from a material decomposed in a small-scale test (LCt_{50}), defined in terms of mass loss exposure dose ($\text{g}\cdot\text{m}^{-3}\cdot\text{min}$)].

NOTE 2 Toxic potency should not be confused with toxic hazard. The latter takes into account other fire parameters such as the rate of mass loss of the burning material and the volume into which toxic effluent is dispersed.

2.27

smoke

visible suspension in atmosphere of solid and/or liquid particles in gases resulting from combustion, pyrolysis or oxidative non-flaming decomposition (see BS 4422-1)

3 Methods available and hazards to be assessed

3.1 Main factors determining hazards to life and health from fire effluent

The development of hazards to life and health from exposure to fire effluent depends upon the rate of fire growth, the amount of effluent evolved, the degree to which the effluent is diluted before a person is exposed and the effects of the effluents on exposed persons. For toxic fire effluent these can be expressed in terms of two major parameters, the first of which relates to the fire itself and the second to the toxic effects, as follows.

- a) The time concentration curves for the major toxic products, which in turn depends upon:
 - 1) the fire growth curve in terms of the mass-loss rate of the fuel ($\text{kg}\cdot\text{s}^{-1}$) and the volume into which it is dispersed ($\text{kg}\cdot\text{m}^{-3}$);
 - 2) the yield of toxic products and smoke in the fire (for example kilograms of CO per kilogram of material burned).

NOTE These two parameters determine the concentrations of toxic gases in the fire effluent.

- b) The toxic potency of the products [the exposure concentration ($\text{kg}\cdot\text{m}^{-3}$ or ppm) or exposure dose ($\text{kg}\cdot\text{m}^{-3}\cdot\text{min}$ or ppm-min) needed to cause toxic effects].

This term requires consideration of three aspects:

- 1) exposure concentrations or doses likely to impair or reduce the efficiency of egress due to psychological or physiological effects;
- 2) exposure concentrations or doses likely to produce incapacitation or prevent egress due to psychological and/or physiological effects; and
- 3) lethal exposure concentrations or doses.

The hazard from smoke obscuration also depends upon the mass loss rate of the fuel, the smoke yield and the degree of obscuration required to affect escape capability [expressed in terms of optical density per metre (OD/m) or similar units]. The hazard from heat depends upon the heat release rate of the fire and the subsequent energy balance of the effluent. The hazard from convected heat is expressed in terms of the air temperature at the exposed skin of the occupant and that from radiant heat in terms of the radiant flux to the exposed skin ($\text{kW}\cdot\text{m}^{-2}$).

Data on these parameters can be obtained in a number of ways, either directly or derived from a particular test and modelling strategy, with varying degrees of confidence depending upon the types of test used.

The most comprehensive method for obtaining the fire parameters is to carry out full scale tests of the situation under investigation or large-scale tests providing a partial simulation. For this method the fire parameters (mass loss rate of the fuel, the volume of dispersal of the effluent, the concentrations of toxic gases, the smoke obscuration, effluent temperature and radiant flux) can all be measured directly. Otherwise, fire data may be obtained indirectly from a variety of sources, usually involving the use of mathematical models of fire growth with small-scale test results as input data.

The third set of data (the toxic potency) has historically been obtained by exposing animals to the mixed test effluents from burning materials, or by studying the toxic effects of individual fire gases in animals and humans. Research in this area has shown that in many cases the major toxic effects are caused by a small number of well known toxic gases, so that toxic potency can now be predicted to a considerable extent based upon existing knowledge, if the concentrations of CO, CO₂, HCN, O₂ and some relevant irritant gases are measured [1] (see also BS ISO TR 9122-5). If these data are available it should be possible to predict the major toxic effects such as time to incapacitation or death for humans (where data relate to full scale tests or fire simulations), or rodents (where analytical data are obtained from small-scale toxicity tests) [2] (see also ISO 13344) without the need for animal tests. However, without animal exposures it is not possible to make a full assessment of irritancy, or to detect unusual acute toxic effects and more subtle long-term effects such as those from halogenated dioxins and dibenzofurans [1] (see also BS ISO TR 9122-6).

NOTE Smoke particulates may also contribute to toxicity by causing breathing difficulties during exposure and contributing to lung inflammation after exposure.

3.2 Practical methods for toxic hazard assessment

Toxic and other hazards to life in fire can be assessed in the following two ways:

- a) from large-scale fire data including the concentration/time profiles of the major toxic gases, smoke obscuration, temperature and radiant heat flux and existing knowledge of the toxic and physiological effects in humans of exposure to these effluent components;

NOTE These data may be obtained directly from large-scale fire tests, from design fire data or from fire data estimated using mathematical models.

- b) from a battery of small-scale tests and mathematical models, or simple large-scale tests, the essential components for a toxic hazard analysis being:

- 1) the toxic potency data for materials [lethal mass loss exposure dose ($\text{g}\cdot\text{m}^{-3}\cdot\text{min}$)] obtained from small-scale tests using animal exposures or analytical methods;
- 2) the mass loss/concentration curve for the fire.

In principle it is possible to treat smoke obscuration in the same way, by measuring smoke yield from a material in a small-scale test and relating it to the mass loss/concentration curve for the fire. It is also possible to predict effluent temperature and radiant flux in a fire from small-scale test data.

The methods described in this part of BS 7899 are intended to be used primarily with the method in a) and to be directly applicable to comprehensive large-scale fire data obtained from large-scale fire tests, design fire data or similar data obtained by a combination of small-scale tests and mathematical models. The second method [see b)] consists of a more simplistic approach, suitable for a preliminary hazard analysis for estimating the performance of materials for which the available data may be more limited.

4 Options and reliability of methods for determining hazard to life

The key to a reliable hazard to life determination is a good model of an appropriate fire scenario. This should include relevant ignition conditions, fire growth and effluent movement within an appropriate enclosure (or set of enclosures within a building). The model should be run beyond the time when the design escape time scenario is complete, or the point where incapacitation is expected to occur. This should therefore encompass several stages of fire growth, possibly including post-flashover conditions. It is particularly important that the ventilation (and therefore oxygen availability) at the various fire stages represents realistic conditions as this has a direct impact on the yields of the major fire gases (including the CO_2/CO ratio) as well as the fire growth rate and the dispersal of the fire effluent. The overall time-concentration curves of the major toxic gases, especially carbon monoxide (and hydrogen cyanide if the fire includes materials containing nitrogen) are particularly important.

A full scale realistic fire test using an appropriate ignition regime, with measurement of all the main fire parameters and with the toxic gases determined by analysis, is the preferred and most reliable procedure. A test of this kind will automatically model a fire through ignition and growth, ensuring that the fire conditions including fuel/air ratios and the CO_2/CO ratios are appropriate throughout.

NOTE It may be appropriate to repeat the test a number of times with different configurations, since quite minor differences in parameters such as the point of ignition or size of ignition source can sometimes cause considerable variations in subsequent hazard development.

Although an adequate assessment of hazard to humans can be made from analytical data on the fire conditions, in some cases animal exposures have been used in addition to gas measurements to test for the presence of unusual toxicants. Current methods of toxic hazard modelling make animal use unnecessary except in exceptional circumstances.

Full scale tests are expensive and for some situations would be very difficult to carry out. In such cases it is usual to rely on simpler tests, sometimes accompanied by hazard calculation modelling. The advantages, disadvantages, reliability and ease of interpreting results with the various test options are summarized in Table 1.

A simpler and less expensive method for making a hazard assessment involves carrying out a full scale test with a restricted set of measurements. A toxic hazard assessment can be made by measuring the mass loss rate (or by measuring the heat release rate and calculating the mass loss rate), and the volume into which the mass is dispersed, in order to obtain a mass loss concentration term ($\text{g}\cdot\text{m}^{-3}$). The mass loss concentration can then be integrated with time to give an estimate of exposure dose with time ($\text{g}\cdot\text{m}^{-3}\cdot\text{min}$). This can then be compared with the lethal or incapacitating exposure dose for the material(s) under investigation obtained from a suitable small-scale toxic potency test using a fire model appropriate to the type of full scale fire obtained. Alternatively, the measurements of the yields of toxic products obtained in the small-scale test can be used to estimate the time-concentration curves for the toxic gases in the full scale fire, so that a full analysis of toxic hazard can be made.

When small-scale tests are used to provide the toxic potency component of the hazard assessment, it is important that the small-scale fire model used for the toxic potency test provides decomposition conditions in terms of fuel/air ratio, flaming behaviour and temperature that are relevant to the fire type used for the full scale test. If the full scale test passes through several fire stages during development, toxic potency data appropriate to each stage should be used (for example potency data obtained from well ventilated flaming during the early stage of a fire and from vitiated or post-flashover flaming during a later stage).

All the above methods should be reasonably reliable as they all involve direct measurement of the fire dynamics (rate of burning and effluent spread). Further methods rely on indirect approaches and are therefore less reliable, although they may be more standardized.

The next stage of simplification or abstraction obtains the mass loss curve and effluent spread by means of empirical generic data and/or mathematical fire modelling. Examples would be the use of slow, medium, fast and ultra fast fire growth curves applied to various fuels, combined with zone or computational fluid dynamics modelling of fire conditions and effluent spread [3], [4], [5], [6], [7] (see also DD 240-1). These can then be combined with toxic potency data for the appropriate fire type [1], [8].

The next stages of simplification rely solely on intermediate or small-scale test data for both the fire dynamics and the toxic potency estimations. Intermediate scale tests can be used to examine the reaction to fire performance of products, particularly during the early stages of fires, but it is essential that care is taken when extrapolating from the intermediate scale to the full scale. If such methods include both ignition and growth stages that are relevant to the full scale, they should overcome some of the problems associated with small-scale tests whilst reducing the costs associated with full scale fire testing. Fire dynamics data obtained from intermediate scale tests can be used with toxic potency data and appropriate mathematical modelling to estimate full scale hazard development to a limited degree.

Small-scale tests of reaction to fire properties are sometimes used in combination with toxic potency data to make simplistic hazard assessments, either using the data as input to mathematical models or in combined indices of product performance. Although such methods may be useful for product development and quality control purposes, considerable difficulties and uncertainties may exist in attempting to relate them to full scale fire hazard [see ISO TR 9122-1 (PD 6503-1) and BS ISO TR 9122-6].

The simplest test methods are those which purport to provide an indication of toxic hazard from a single small-scale test. Such tests often rely on very unrealistic fire models and inaccurate measurement methods combined with inappropriate methods for toxic potency assessments to produce indices of toxicity or toxic hazard. The results of such tests are likely to provide a misleading indication of full scale hazard to life (see BS ISO TR 9122-4 and -6).

It should therefore be apparent that a good understanding of fire processes is important in carrying out fire hazard assessments. A full scale test involving a realistic fire scenario can be used to provide a direct measurement of hazard to life. However, the number of variables involved in full scale fires is large so that small changes in any full scale scenario can result in a range of hazard development rates. Assessments based upon small-scale tests involve much greater uncertainties and require much more expert interpretation than full scale tests to avoid misunderstanding and misleading conclusions. Some small-scale tests used quite widely in industry for product specification are likely to produce misleading indications of likely full scale hazards.