INTERNATIONAL STANDARD

ISO 24678-2

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Fire safety engineering — Requirements governing algebraic formulae —

Part 2: **Fire plume**

Ingénierie de la sécurité incendie — Exigences régissant les formules algébriques —

Partie 2: Panaches de feu

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

This first edition cancels and replaces ISO 16734:2006, which has been technically revised.

The main changes are as follows:

— the main body has been simplified by making reference to ISO 24678-1;

— comparisons with experimental data have been added in Annex A;

— Annex B has been added to describe input data on the fire source.

A list of all parts in the ISO 24678 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The ISO 24678 series is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. It is expected that the users of this document are appropriately qualified and competent in the field of fire safety engineering. It is particularly important that users understand the parameters within which particular methodologies may be used.

Algebraic formulae conforming to the requirements of this document are used with other engineering calculation methods during a fire safety design. Such a design is preceded by the establishment of a context, including the fire safety goals and objectives to be met, as well as performance criteria when a trial fire safety design is subject to specified design fire scenarios. Engineering calculation methods are used to determine if these performance criteria are met by a particular design and if not, how the design needs to be modified.

The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles, as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document can be useful for estimating the consequences of design fire scenarios. Such formulae are valuable for allowing the practitioner to quickly determine how a proposed fire safety design needs to be modified to meet performance criteria and to compare among multiple trial designs. Detailed numerical calculations can be carried out up until the final design documentation. Examples of areas where algebraic formulae have been applicable include determination of convective and radiative heat transfer from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings, and analysis of compartment fire hazards such as smoke filling and flashover. However, the simple models often have stringent limitations and are less likely to include the effects of multiple phenomena occurring in the design scenarios.

The general principles of fire safety engineering are described in ISO 23932-1, which provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property and the environment. ISO 23932-1 provides the process (i.e. necessary steps) and essential elements for conducting a robust performance-based fire safety design.

ISO 23932-1 is supported by a set of fire safety engineering documents on the methods and data needed for all the steps in a fire safety engineering design as summarized in Figure 1 (taken from ISO 23932-1:2018, Clause 4). This set of documents is referred to as the Global fire safety engineering analysis and information system. This global approach and system of standards provides an awareness of the interrelationships between fire evaluations when using the set of fire safety engineering documents. The set of documents includes ISO/TS 13447, ISO 16730-1, ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-1, ISO 24679-1, ISO/TS 29761 and other supporting Technical Reports that provide examples of and guidance on the application of these documents.

Each document supporting the global fire safety engineering analysis and information system includes language in the introduction to tie that document to the steps in the fire safety engineering design process outlined in ISO 23932-1. ISO 23932-1 requires that engineering methods be selected properly to predict the fire consequences of specific scenarios and scenario elements (ISO 23932:2018, Clause 12). Pursuant to the requirements of ISO 23932-1, this document provides the requirements governing algebraic formulae for fire safety engineering. This step in the fire safety engineering process is shown as a highlighted box in Figure 1 and described in ISO 23932-1.
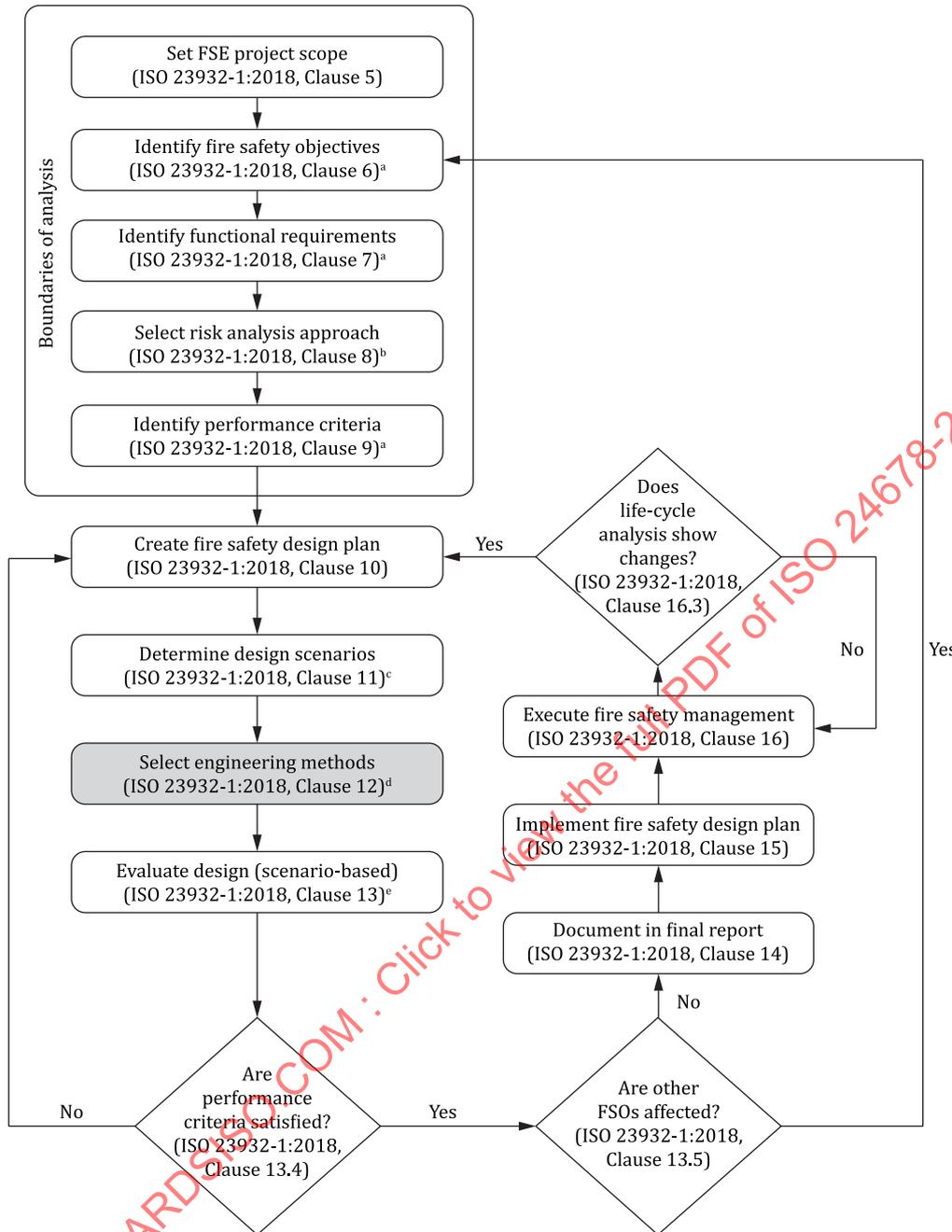
a   See also ISO/TR 16576 (Examples).

b   See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

c   See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

d   See also ISO/TS 13447, ISO 16730-1, ISO/TR 16730-2 to ISO/TR 16730-5 (Examples), ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-1, ISO 24678-2 (this document), ISO 24678-6 and ISO 24678-7.

e   See also ISO/TR 16738, ISO 16733-1, ISO/TS 16733-2.

NOTE   Documents linked to large parts of the fire safety engineering process: ISO 16732-1, ISO 16733-1, ISO 24679-1, ISO/TS 29761, ISO/TR 16732-2 to ISO/TR 16732-3 (Examples), ISO/TR 24679-2 to ISO/TR 24679-4 and ISO/TR 24679-6 (Examples).

Figure 1 — Flow chart illustrating the fire safety engineering design process (from ISO 23932-1:2018)

Fire safety engineering — Requirements governing algebraic formulae —

Part 2:
Fire plume

1 Scope

This document specifies the requirements governing the application of a set of explicit algebraic formulae for the calculation of specific characteristics of fire plume.

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 13943, *Fire safety — Vocabulary*

ISO 24678-1, *Fire safety engineering — Requirements governing algebraic formulae — Part 1: General requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following 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
axisymmetric
in a state in which mean motion and properties, such as mean temperature rise, are symmetric with respect to a vertical centreline

3.2
characteristic plume radius
radius at which the time-average plume temperature rise above the ambient value is one half the centreline value

3.3
convective fraction of heat release rate
ratio of the convective heat release rate to the total heat release rate

3.4
convective heat release rate
component of the heat release rate carried upward by the fire plume motion

Note 1 to entry: Above the mean flame height, this component is considered invariant with height.

3.5
entrained mass flow rate
air drawn in from the surroundings into the fire plume

Note 1 to entry: The mass flow rate in the plume at a given level can be considered equal to the mass flow rate of air entrained below that level into the plume. The fire source contributes an insignificant mass to the plume flow, typically less than 1 % of the total at the mean flame height.[28]

3.6
fire source diameter
effective diameter of the fire source, equal to the actual diameter for a circular source or the diameter of a circle having an area equal to the plan area of a non-circular source

3.7
fuel mass burning rate
mass generation rate of fuel vapours

3.8
mean flame height
time-average height of flames above the base of a fire, defined as the elevation where the probability of finding flames is 50 %

3.9
mean temperature rise
time-average gas temperature rise above the ambient value

3.10
mean vertical gas velocity
time-average velocity of vertical gas motion on the plume centreline

3.11
quasi-steady state
state in which it is assumed that the full effects of heat release rate changes at the fire source are felt everywhere in the flow field immediately

3.12
radiant energy release factor
ratio of the combustion heat released in a fire as thermal radiation to the net heat of combustion

3.13
virtual origin
point source from which the fire plume above the flames appears to originate

Note 1 to entry: The location of the virtual origin is likely to be above the fire source for the case of flammable liquid pool fires having a diameter of approximately 10 m or less and below the fire source for pool diameters larger than 10 m to 20 m.

4 Requirements governing the description of physical phenomena

4.1 The requirements governing the description of physical phenomena apply as specified in ISO 24678-1 in addition to the following.

4.2 The fire plume resulting from a fire source is a complex, thermo-physical phenomenon that can be highly transient or nearly steady-state. It contains regions closer to the fire source where there is usually flaming combustion (unless the source is a smouldering fire) and regions farther from the source where there is no combustion taking place, but a turbulent upward flow dominated by buoyancy forces. Regions of the fire plume (whether or not flaming/combusting, degree of fire source influence, etc.) to which specific formulae apply shall be clearly identified.

4.3   The fire plume can be significantly affected by many environmental parameters, e.g. the nature and arrangement of the burning materials that act as a fire source; whether there is flaming or smouldering combustion; degree of air restriction or vitiation; wind flows or compartment air motion; etc. For a liquid hydrocarbon fire burning in the open under calm (windless) conditions, the problem of describing the fire plume by algebraic formulae is simplified since most of these environmental parameters have a negligible influence. General types of source fires, flow-boundary (including symmetry) conditions and other scenario elements to which the analysis is applicable shall be described with the aid of diagrams.

5   Requirements governing the calculation process

The requirements specified in ISO 24678-1 governing the calculation process apply.

6   Requirements governing limitations

The requirements specified in ISO 24678-1 governing limitations apply.

7   Requirements governing input parameters

The requirements specified in ISO 24678-1 governing input parameters apply.

8   Requirements governing the domain of applicability

The requirements specified in ISO 24678-1 governing the domain of applicability apply.

9   Example of documentation

An example of sets of algebraic formulae meeting the requirements in Clauses 4-8 is provided in annexes. Annex A contains a set of algebraic formulae for a fire plume from a circular or near-circular fire source in a quiescent environment. Annex B contains information on input data on fire source properties.

Annex A
(informative)

Formulae for quasi-steady, axisymmetric fire plumes from a circular or near-circular fire source

A.1 General

This annex describes a set of formulae for axisymmetric fire plume. Properties such as flame height, mass flow rates, temperature distribution are calculated. The fire source can be circular or near-circular shape.

A.2 Symbols used in Annex A

A_s plan area of fire source (m^2)

$b_{\Delta T}$ characteristic plume radius where the mean temperature rise is one-half the centreline value (m)

c_p specific heat of air at constant pressure (kJ/kg·K)

D fire source diameter (m)

g acceleration due to gravity (m/s^2)

ΔH_c net heat of combustion of fire source material (kJ/kg)

L mean flame height above base of fire source (m)

$\dot{m}_{ent}$ entrained mass flow rate (kg/s)

$\dot{m}_{ent,L}$ entrained mass flow rate at the mean flame height (kg/s)

$\dot{m}_f$ fuel mass burning rate (kg/s)

N non-dimensional parameter, as defined in A.4.2

$\dot{Q}$ heat release rate from fire source (kW)

$\dot{Q}_c$ convective heat release rate from fire source (kW)

s stoichiometric mass ratio of air to fuel

T_0 mean temperature on plume centreline (K)

T_{0L} mean temperature on plume centreline at mean flame height (K)

T_a ambient temperature (K)

u_0 mean vertical gas velocity on plume centreline (m/s)

z height above base of fire source (m)

z_v height of virtual origin above base of fire source (m)

ΔT_0 mean temperature rise above ambient on plume centreline (K)

ΔT_{0L} mean temperature rise on plume centreline at mean flame height (K), typically 500 K

ΔT_{ave} spatial-average plume temperature rise at or above mean flame height (K)

α convective fraction of heat release rate, $1 - \chi_R / \chi_a$, typically 0,6 to 0,7

ρ_a density of ambient air (kg/m^3)

χ_a combustion efficiency factor

χ_R radiant energy release factor

A.3   Description of physical phenomena addressed by the formula set

A.3.1   General description of the calculation method

A.3.1.1   Calculation procedure

Estimating the fire plume properties involves the following steps:

— determination of characteristics of the fire source (burning fuel surface, mass burning rate, etc.);

— determination of flame height;

— calculation of centreline temperature and mass flow rate at and above mean flame height.

A.3.1.2   Fire plume characteristics to be calculated

The formula set provides gas temperatures and velocities for locations along the plume vertical centreline (symmetry axis). Mean flame height, plume entrained mass flow rate and characteristic radius based on the rise in gas temperature and average plume temperature rise are also calculated.

A.3.1.3   Fire plume regions to which formulae apply

A distinction is made between regions above the mean flame height and regions below the mean flame height in the fire plume, with formulae applicable to the region above only.

A.3.2   Scenario elements to which the formula set is applicable

The formula set is applicable to plumes rising above quasi-steady state fire sources that are approximately circular or square in plan area in a quiescent environment (i.e. burning is without interference from active protection measures, wind, etc.). The fire source is a horizontal, upward-facing burning fuel surface or a three-dimensional burning array for which the mean flame height is greater than the array height. Applicable fire sources include those outside of enclosed spaces, those inside of enclosed spaces (when the fire source itself and its flames are remote from the boundaries of the enclosed space). An applicable fire source can also consist of a built environment fully involved in fire, when the mean flame height due to flames burning through the top of the built environment (e.g. a collapsed roof) is greater than the height of the built environment. See Clause A.6 for quantitative limitations on these scenario elements.

A.3.3   Self-consistency of the formula set

The formula set provided in this annex has been derived and reviewed by G. Heskestad[29] (see Clause A.5) to ensure that calculations resulting from different formulae in the set are consistent (i.e. do not produce conflicts).

A.3.4 International Standards and other documents where the formula set is used

Formulae (A.4), (A.9) and (A.18) are used in NFPA 204[30] for smoke and heat venting.

A.4 Formula set: documentation of calculation process

A.4.1 General description of axisymmetric plumes

Properties of axisymmetric, quasi-steady state fire plume as shown in Figure A.1 are considered. Mean flame height, centreline velocity and temperature rise at and above mean flame height are calculated.
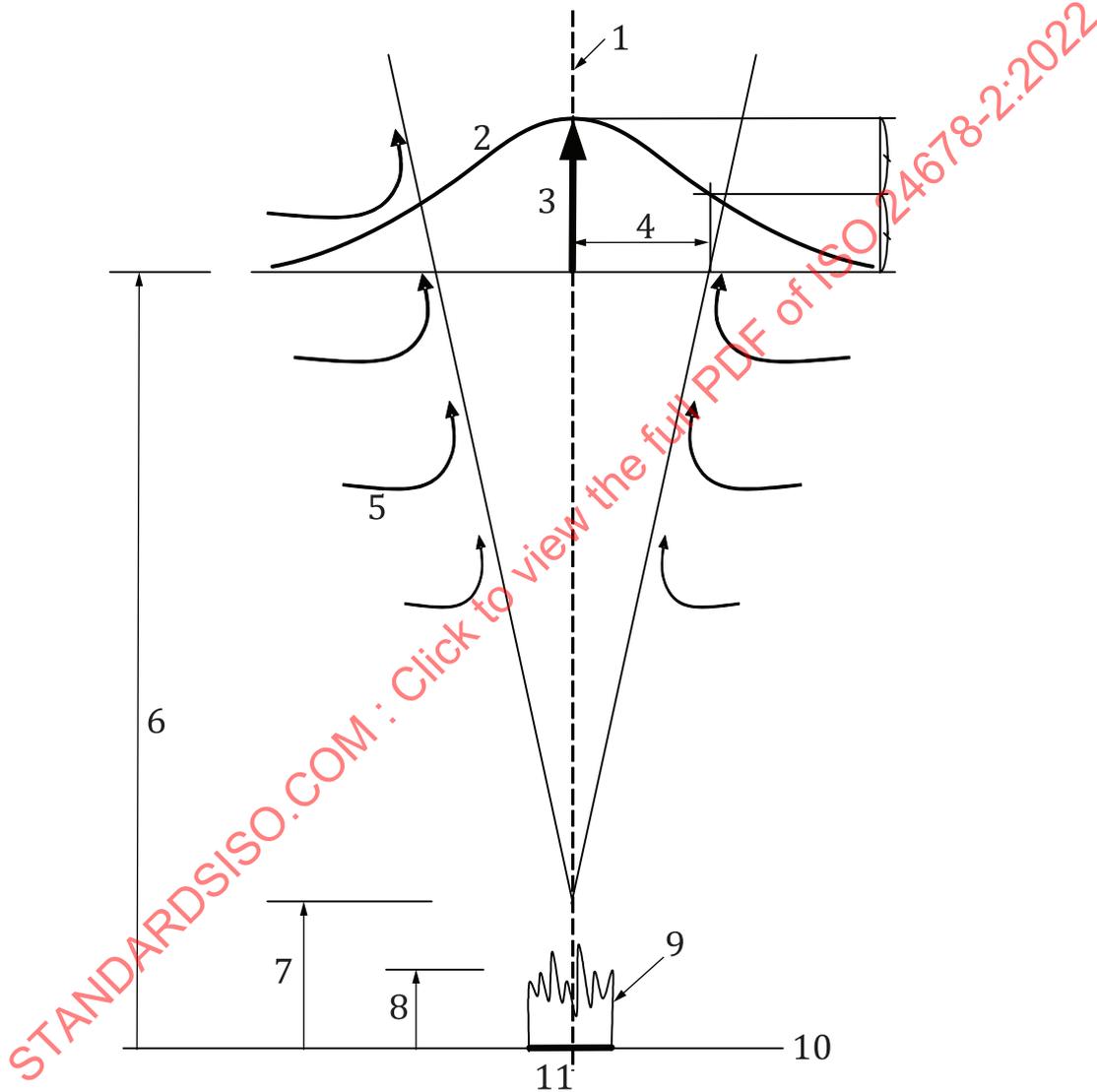
Key

1	centreline	7	height of virtual origin
2	velocity profile	8	mean flame height
3	centreline velocity	9	flame
4	characteristic plume radius	10	base of fire source
5	air entrainment	11	plan area of fire source
6	height above base of fire source		

Figure A.1 — Illustration of parameters describing the plume flow

A.4.2 Mean flame height

The dimensionless formulation for mean flame height, L/D, is given by Formulae (A.1) to (A.3)[31] and is applicable to a wide range of atmospheric and fuel conditions relevant to fires in the built environment.

$$\frac{L}{D} = -1,02 + 15,6N^{1/5} \tag{A.1}$$

$$N = \left[\frac{c_p T_a}{g\rho_a^2 (\Delta H_c/s)^3} \right] \frac{\dot{Q}^2}{D^5} \tag{A.2}$$

$$\dot{Q} = \dot{m}_f \chi_a \Delta H_c \tag{A.3}$$

Under normal atmospheric conditions:

— g = 9,81 m/s^2;

— c_p = 1,01 kJ/(kg·K);

— ρ_a = 1,2 kg/m^3;

— T_a = 293 K;

and using $\Delta H_c/s$ = 3 000 kJ/kg as an average for many common fuels,[32] the mean flame height, L, is given by Formula (A.4)[29]:

$$L = -1,02D + 0,235\dot{Q}^{2/5} \tag{A.4}$$

A.4.3 Height of virtual origin above the fire source

The dimensionless formulation for virtual origin height, z_v/D, is given by Formulae (A.5) to (A.8)[33] and is applicable to a wide range of atmospheric and fuel conditions relevant to fires in the built environment:

$$\frac{z_v}{D} = -1,02 + 15,6(X-Y)\frac{\dot{Q}^{2/5}}{D} \tag{A.5}$$

$$X = \left[\frac{c_p T_a}{g\rho_a^2 (\Delta H_c/s)^3} \right]^{1/5} \tag{A.6}$$

$$Y = 0,158\left[(c_p \rho_a)^{4/5} T_a^{3/5} g^{2/5} \right]^{-1/2} \alpha^{2/5} \frac{T_{0L}^{1/2}}{\Delta T_{0L}^{3/5}} \tag{A.7}$$

$$T_{0L} = \Delta T_{0L} + T_a \tag{A.8}$$

Under normal atmospheric conditions as determined in A.4.2, and using:

— α = 0,7

— ΔT_{0L} = 500 K

— $\Delta H_c/s$ = 3 000 kJ/kg

as an average for many common fuels,[32] the height of virtual origin above the base of the fire source, z_v, in terms of $\dot{Q}$ and D is given by Formula (A.9).[33] The dimensional correlation is not sensitive to fuel type:

$$\frac{z_v}{D} = -1,02 + 0,083\frac{\dot{Q}^{2/5}}{D} \tag{A.9}$$

Under normal atmospheric conditions as determined in A.4.2, and using:

— ΔT_{0L} = 500 K

— $\Delta H_c/s$ = 3 000 kJ/kg

the height of virtual origin above the base of the fire source, z_v, in terms of $\dot{Q}_c$ and L is given by Formulae (A.10) and (A.11).[33] The dimensional correlation is not sensitive to fuel type:

$$z_v = L - 0,175\dot{Q}_c^{2/5} \tag{A.10}$$

$$\dot{Q}_c = \alpha\dot{Q} \tag{A.11}$$

A.4.4 Mean centreline temperature rise at and above the mean flame height

The dimensionless formulation for mean centreline temperature rise, ΔT_0, at and above the mean flame height is given by Formula (A.12):[34]

$$\Delta T_0 = 9,1\left(\frac{T_a}{gc_p^2\rho_a^2}\right)^{1/3}\dot{Q}_c^{2/3}(z-z_v)^{-5/3} \tag{A.12}$$

Under normal atmospheric conditions as determined in A.4.2, the mean centreline temperature rise, ΔT_0, at and above the mean flame height is given by Formula (A.13):[32]

$$\Delta T_0 = 25,0\dot{Q}_c^{2/3}(z-z_v)^{-5/3} \tag{A.13}$$

A.4.5 Mean centreline vertical gas velocity at and above the mean flame height

The dimensionless formulation for mean vertical gas velocity on the plume centreline, u_0, at and above the mean flame height is given by Formula (A.14):[34]

$$u_0 = 3,4\left(\frac{g}{c_p\rho_aT_a}\right)^{1/3}\dot{Q}_c^{1/3}(z-z_v)^{-1/3} \tag{A.14}$$

Under normal atmospheric conditions as determined in A.4.2, the mean vertical gas velocity, u_0, at and above the mean flame height is given by Formula (A.15), a dimensional correlation:[29]

$$u_0 = 1,03\dot{Q}_c^{1/3}(z-z_v)^{-1/3} \tag{A.15}$$

A.4.6 Characteristic plume radius at and above the mean flame height

The dimensionless formulation for the characteristic plume radius where the mean temperature rise is one-half the centreline value, $b_{\Delta T}$, is given by Formula (A.16):[34]

$$b_{\Delta T} = 0,12\left(\frac{T_0}{T_a}\right)^{1/2}(z-z_v) \tag{A.16}$$

NOTE   The plume radius to the point where the gas velocity is one-half the centreline value is about 10 % larger than the plume radius, $b_{\Delta T}$, to the point where the mean temperature rise is one-half the centreline value.

A.4.7   Entrained mass flow rate at and above the mean flame height

The dimensionless formulation for the entrained mass flow rate, $\dot{m}_{ent}$, at and above the mean flame height is given by Formula (A.17):[28],[31]

$$\dot{m}_{ent} = 0,196 \left(\frac{g\rho_a^2}{c_p T_a} \right)^{1/3} \dot{Q}_c^{1/3} (z - z_v)^{5/3} \left[1 + \frac{2,9\dot{Q}_c^{2/3}}{\left(g^{1/2} c_p \rho_a T_a \right)^{2/3} (z - z_v)^{5/3}} \right] \tag{A.17}$$

Under normal atmospheric conditions as determined in A.4.2, the entrained mass flow rate at and above the mean flame height is given by Formula (A.18), a dimensional correlation:[29]

$$\dot{m}_{ent} = 0,071 \dot{Q}_c^{1/3} (z - z_v)^{5/3} [1 + 0,027 \dot{Q}_c^{2/3} (z - z_v)^{-5/3}] \tag{A.18}$$

The dimensionless formulation for the entrained mass flow rate at the mean flame height, $\dot{m}_{ent,L}$, [$z = L$ and z_v from Formulae (A.5) to (A.8), substituted in Formula (A.17)] is given by Formula (A.19):[29]

$$\dot{m}_{ent,L} = 0,878 \left[\left(\frac{T_{0L}}{T_a} \right)^{5/6} \left(\frac{T_a}{\Delta T_{0L}} \right) + 0,647 \right] \frac{\dot{Q}_c}{c_p T_a} \tag{A.19}$$

The entrained mass flow rate at the mean flame height, $\dot{m}_{ent,L}$, under normal atmospheric conditions as determined in A.4.2, and with ΔT_{0L} = 500 K, is given by Formula (A.20), a dimensional correlation from Reference [29]:

$$\dot{m}_{ent,L} = 0,005\,9\,\dot{Q}_c \tag{A.20}$$

A.4.8   Spatial-average plume temperature rise at and above the mean flame height

The spatial-average plume temperature rise at and above the mean flame height, ΔT_{ave}, is given by Formula (A.21):[29]

$$\Delta T_{ave} = \frac{\dot{Q}_c}{\dot{m}_{ent}\,c_p} \tag{A.21}$$

A.5   Scientific basis for the formula set

The theory of axisymmetric fire plumes traces to early theories by Schmidt,[35] Rouse et al.,[36] Morton et al.[37] and Yokoi,[38] with refinements for large density deficiencies by Morton,[39] and empirical coefficients established by Heskestad[29] from published experiments. The formulae for virtual origin, z_v, was developed by Heskestad,[33] with consideration of work by other authors, including Hasemi and Tokunaga[40] and Cetegen et al..[41] The flame height formulae traces back to Heskestad.[31] Contributions to prediction of entrainment have been made by Yih,[42] Thomas et al.,[43] McCaffrey,[44] Cetegen et al.,[45] Heskestad,[31] Delichatsios,[46] Zukoski [47] and Zhou and Gore.[48]

A number of authors have also addressed conditions arising in axisymmetric fire plumes, including Cox and Chitty,[49] Dai et al.,[50] Gengembre et al.,[51] George et al.,[52] Heskestad,[53-55] Kung and Stavrianidis,[56] McCaffrey,[57] Orloff,[58] Orloff and de Ris,[59] Shabbir and George,[60] Tamanini [61] and Thomas.[62],[63]

The basis for formulae in subclauses A.4.1 through A.4.6 is documented by Heskestad.[29] Formulae (A.19) and (A.20) are derived by Heskestad[29] using the formulae in A.4.2 and A.4.3.

A.6 Formula set limitations

A.6.1 Fire sources

The formula set should not be applied to fire sources that are:

— affected by extinguishing agents;

— rectangular fire sources having a length-to-width ratio greater than or equal to 2;

— three-dimensional fire sources having restricted air access or a mean flame height less than 110 % of the height of the three-dimensional source itself;

— fire sources consisting of a jet flame (such as from a pipe-leak or flow through an orifice from a pressurized fuel reservoir);

— fire sources consisting of flames distributed to such an extent over the source area that there are multiple fire plumes.

A.6.2 Flame dimensions

The formula-set should not be applied within enclosed spaces, when the mean flame height, L, is greater than 50 % of the vertical interior dimension of the enclosed space and/or when the effective fire source diameter, D, is greater than 10 % of the minimum plan dimension of the enclosed space.

A.6.3 Proximity to boundaries

The formula set should not be applied within enclosed spaces, when the fire source itself or its flames are within one fire source diameter, D, of a boundary surface.

A.6.4 Aerodynamic disturbances

The formula set should not be applied to plumes that are affected by aerodynamic disturbances, which can arise from obstructions in the flow field or from the effects of wind, forced ventilation or natural ventilation through enclosure openings.

A.6.5 Output parameters

The formula set should not be applied when the calculated mean temperature rise, ΔT_0, is much less (see A.7.7) than the temperature rise with elevation in the environment before fire initiation (e.g. between the top and bottom of an enclosed space due to temperature stratification) or when the calculated mean temperature rise is greater than ΔT_{0L}.

A.7 Formula-set input parameters

A.7.1 Fire heat release rate

The parameter, $\dot{Q}$, expressed in kilowatts, is the rate of heat actually released by a fire under specific environmental conditions, as measured by a calorimeter that is based on product gas collection to determine O_2, CO_2 and CO generation rates, or as otherwise specified. This parameter is normally obtained from the design fire scenario. Additional sources of information on fire heat release rate and fire calorimetry include Khan and Tewarson[32] and Babrauskas.[64] Annex B provides information on reaction-to-fire test methods available to develop input data on fire sources.

A.7.2 Convective fraction

The dimensionless parameter, α, is typically in the range of 0,6 to 0,7 for exposed solid surfaces or liquid fuels burning in a pool but can be up to 0,8 or greater for oxygenated liquid fuels or for low-molecular-weight gaseous fuels. For three-dimensional fire sources, the parameter is much less than unity early

in the fire growth period, increasing to 0,6 to 0,7 during the advanced stages of fire growth. This parameter is normally obtained from the design fire scenario, but additional information is available from Khan and Tewarson.[32]

A.7.3   Fire source diameter

The parameter, D, expressed in m, is the diameter for a circular fire source. This parameter is normally obtained from the design fire scenario. For rectangular fire sources, an effective diameter, D, is obtained from Formula (A.22), which uses a circular source having the same plan area, A_s, expressed in m², as the fire source:

$$D = \sqrt{\frac{4A_s}{\pi}}$$
(A.22)

Supplemental information is found in Annex B.

A.7.4   Height in the fire plume

The parameter, z, expressed in m, is normally obtained from the design fire scenario.

A.7.5   Heat of combustion per unit mass of air

The parameter $\Delta H_c/s$, expressed in kJ/kg, for specific polymers and other materials can be obtained from Khan and Tewarson[32] (with the latter values adjusted for combustion efficiency), Babrauskas[64] and the Chemical Engineers' Handbook.[65] The parameter $\Delta H_c/s$ for fuels not listed in the preceding references can require testing that involves the use of a calorimeter to determine ΔH_c and elemental analysis to determine s.

A.7.6   Valid ranges for input parameters

The heat release rate and diameter parameters, $\dot{Q}$ and D, respectively, should normally satisfy the inequality condition in Formula (A.23), based on information in McCaffrey:[57]

$$0,04 < \frac{\dot{Q}}{\rho_a c_p T_a \sqrt{g} D^{5/2}} < 2 \times 10^4$$
(A.23)

The valid range for the parameter, z, is normally from the mean flame height to either the elevation of the top surface of an enclosed space or a value corresponding to a temperature rise meeting the requirements of A.7.7.

A.7.7   Temperature stratification

Temperature stratification in the ambient environment is limited such that the ambient temperature, T_a, at height, z, is related to ambient temperature near the base of the fire, $(T_a)_{z=0}$ as given by the inequality condition in Formula (A.24).[29]

$$(T_a)_z - (T_a)_{z=0} < 7\Delta T_0$$
(A.24)

## A.8   Domain of applicability of the formula set

A.8.1   General

The domain of applicability of the formula set laid out in this annex can be determined from the scientific literature references given in Clause A.5.

A.8.2 Comparison with experimental data

A.8.2.1 Flame height

Formula (A.4) is compared with experimental data as shown in Figure A.2. The fire source strength $Q/D^{5/2}$ is in the range of 24 to 41 600 kW/m$^{5/2}$. Good agreement is obtained if the source strength is more than 200 kW/m$^{5/2}$. For a low-strength fire source, the data scatters because the fire plume is weak and non-uniform.
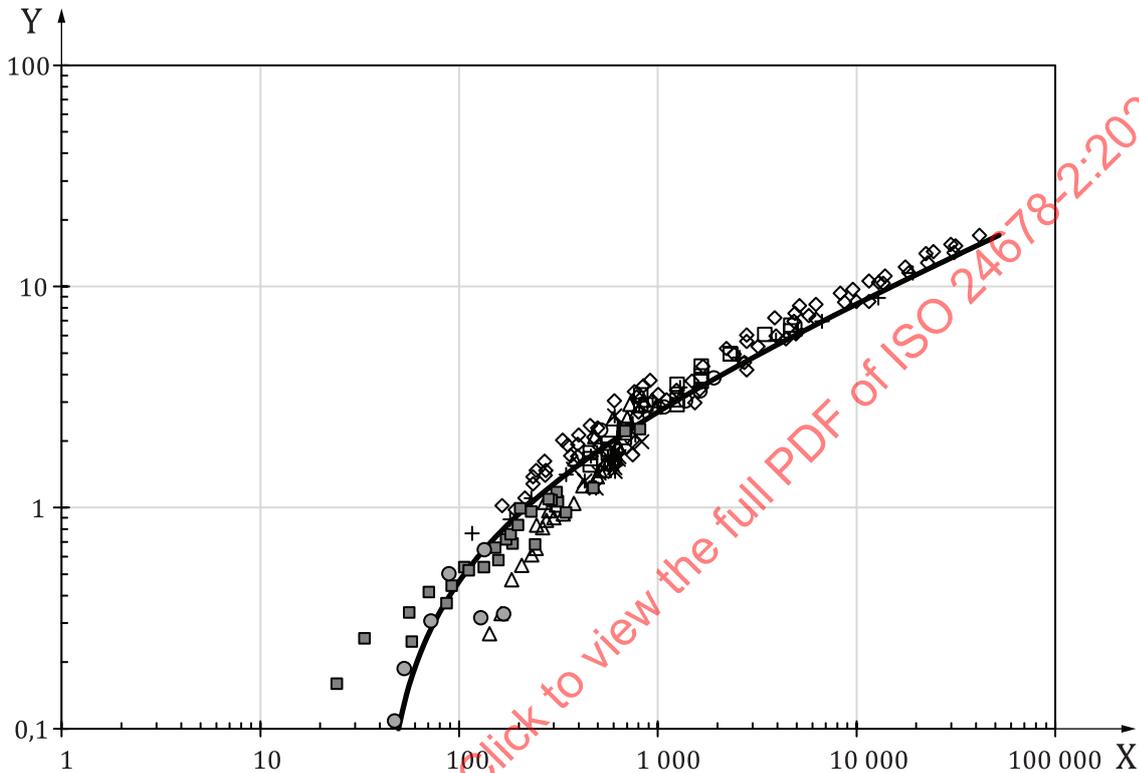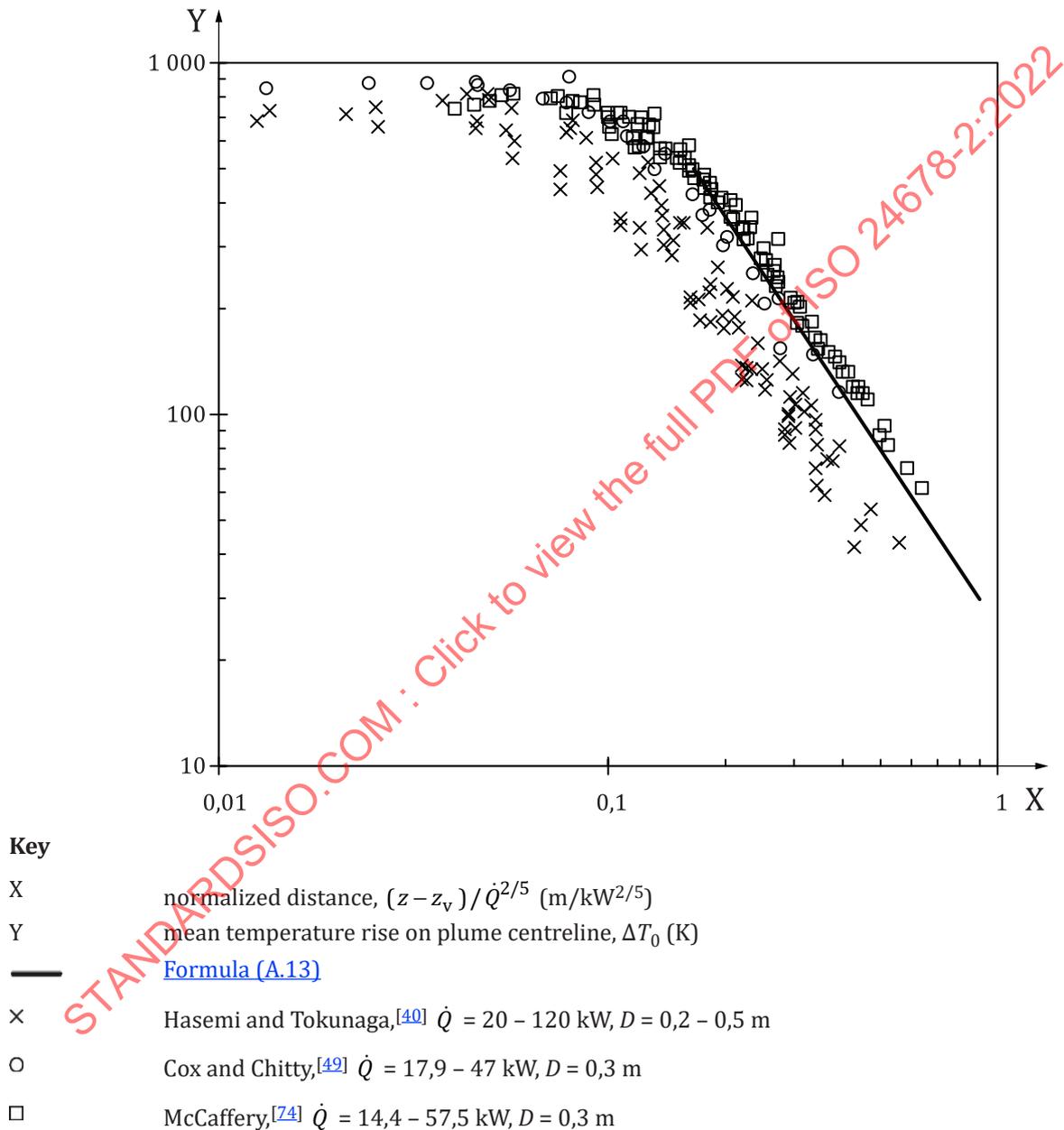

Key

X		fire source strength, $\dot{Q}/D^{5/2}$ (kW/m$^{5/2}$)
Y		non-dimensional flame height, L/D
▬		Formula (A.4)
◇		Zukoski, Kubota and Cetegen,[66] $\dot{Q}$ = 10 – 200 kW, D = 0,1 – 0,5 m
△		Cox and Chitty,[67] $\dot{Q}$ = 45,6 – 118 kW, D = 0,6 m
✕		Terai and Nitta,[68] $\dot{Q}$ = 1,1 – 17,4 kW, D = 0,71 – 0,306 m
✳		Poreh and Garrad,[69] $\dot{Q}$ = 20 – 800 kW, D = 0,5 – 1,0 m
○		Shintani et al.,[70] $\dot{Q}$ = 24,9 – 140 kW, D = 0,25 m
□		Hasemi and Tokunaga,[40] $\dot{Q}$ = 20 – 120 kW, D = 0,2 – 0,5 m
+		Cetegen, Zukoski and Kubota,[71] $\dot{Q}$ = 19 – 52 kW, D = 0,1 – 0,5 m
◼		Hasemi and Nishihata,[72] $\dot{Q}$ = 11 – 443 kW, D = 0,2 – 1,52 m
⬤		Wood, Blackshear and Eckert [73]

Figure A.2 — Comparison of mean flame height with experiments

A.8.2.2 Mean temperature rise on plume centreline

Formula (A.13) is compared with experimental data as shown in Figure A.3. McCaffery[74] measures the mean centreline temperature rise of pool fires with 0,3 m diameter. The heat release rate is in the range of 14,4 to 57,5 kW. Cox and Chitty[49] measure at heat release rate of $\dot{Q}$ = 17,9 – 47 kW. The fire source diameter is D = 0,3 m as well. Both results agree well with Formula (A.13). Hasemi and Tokunaga[40] measure centreline temperatures of propane gas fires in a wide range of diameters and heat release rates. The diameter is varied from 0,2 m to 0,5 m. The heat release rate is 20 kW to 120 kW. The measured results are slightly lower than the values calculated by Formula (A.13).

Key

X	normalized distance, $(z - z_v)/\dot{Q}^{2/5}$ (m/kW$^{2/5}$)
Y	mean temperature rise on plume centreline, ΔT_0 (K)
——	Formula (A.13)
×	Hasemi and Tokunaga,[40] $\dot{Q}$ = 20 – 120 kW, D = 0,2 – 0,5 m
○	Cox and Chitty,[49] $\dot{Q}$ = 17,9 – 47 kW, D = 0,3 m
□	McCaffery,[74] $\dot{Q}$ = 14,4 – 57,5 kW, D = 0,3 m

Figure A.3 — Comparison of mean temperature rise on plume centreline with experiments

A.9   A calculation example

A.9.1   Calculation condition

Consider a circular 1,8 m diameter pan of a flammable liquid burning at a heat release rate of 2 500 kW under normal atmospheric conditions as determined in A.4.2.

A.9.2   Mean flame height

The mean flame height, L, expressed in m, is obtained by Formula (A.25) [based on Formula (A.4)] as follows:

$$L = -1,02D + 0,235Q^{2/5}$$
$$= -1,02 \times 1,8 + 0,235 \times 2\,500^{2/5} = 3,54 \tag{A.25}$$

A.9.3   Height of virtual origin

Since the heat release rate is given, the height of virtual origin, z_v, expressed in m, is obtained by Formula (A.26) [based on Formula (A.9)] as follows:

$$z_v = -1,02D + 0,083\dot{Q}^{2/5}$$
$$= -1,02 \times 1,8 + 0,083 \times 2\,500^{2/5} = 0,062 \tag{A.26}$$

which means that the virtual origin is 0,062 m above the base of fire source.

A.9.4   Mean centreline temperature rise at and above the mean flame height

The convective fraction of heat release rate is assumed to be 0,7. The mean centreline temperature rise on the plume centreline, above the ambient value, at 9 m above the flammable liquid surface is obtained by Formula (A.27) [based on Formula (A.13)] as follows:

$$\Delta T_0 = 25,0\dot{Q}_c^{2/3}(z - z_v)^{-5/3}$$
$$= 25 \times (0,7 \times 2\,500)^{2/3} \times (9,0 - 0,062)^{-5/3} = 94,3 \tag{A.27}$$

where ΔT_0 is expressed in K.

Annex B
(informative)

Input data on fire sources for calculations of fire plume properties

B.1 General

This annex provides guidance for input data on fire sources for the calculation of fire plume properties.

B.2 Symbols used in Annex B

A_s plan area of fire source (m^2)

d thickness of fire source material (m)

D fire source diameter (m)

$\dot{Q}$ heat release rate from fire source (kW)

$\dot{Q}''$ heat release rate per unit plan area of fire source (kW/m^2)

r_b radius of burnt-out area (m)

r_f radius of flame spread area (m)

t time (s)

v_f surface flame spread rate (m/s)

z height above base of fire source (m)

z_s height of fire source above floor (m)

ΔH_c net heat of combustion of fire source material (kJ/kg)

ρ density of fire source material (kg/m^3)

B.3 Input data elements for calculation

For the calculation of fire plume properties, geometry of fuel and heat release rate are required as shown in Table B.1.

Table B.1 — Data requirements for calculations

Data element	Description	Unit	Source
fire source diameter, D	outer diameter of burning area	m	experimental observations of burning
height of base of fire source, z_s	height of principal burning plane above floor	m	experimental observations of burning
heat release rate, $\dot{Q}$	heat released by combustion of fuel per unit time	kW	bench scale and/or full-scale testing method(s)

B.4 Fire source geometry

The fire source diameter is characterized by D, and the height of fire source by z_s. For realistic burning items, the geometry is determined by direct observation during burning as shown in Figure B.1. The plan area of fire source, A_s, is determined by visual observation. The fire source diameter is then calculated by a circular plane with equivalent area by Formula (B.1):

$$D = \sqrt{\frac{4A_s}{\pi}}$$

(B.1)

The height of fire source is also determined by visual observation. As shown in Figure B.1, the base of fire source is located at the bottom of the principal burning area.
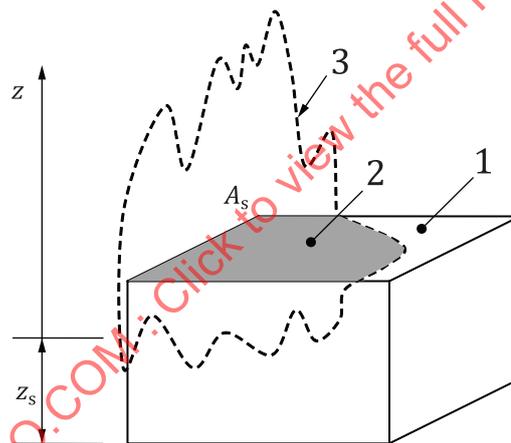
Key
1   burning object
2   plan area of fire source, A_s
3   flame

Figure B.1 — An example of characterizing source geometry

B.5 Heat release rate

B.5.1 Direct measurements of heat release rate

Heat release rate can be measured by various methods. For direct application to a calculation, the heat release rate can be measured by a burning test of a full-scale specimen. One of the appropriate methods is oxygen consumption calorimetry as determined by ISO 24473.

B.5.2 Estimation of heat release rate using bench scale measurements

ISO/TS 3814 gives general guidance on reaction-to-fire test methods. ISO/TR 17252 describes available test methods to derive physical parameters for use in fire modelling and fire safety engineering. The ISO 5660-1 cone calorimeter test gives fundamental information on heat release of materials from a 100 mm square specimen. ISO 14696 gives information on heat release from a 1 m^2 specimen that can accommodate joints. ISO 12136 gives information on heat release by small specimen in various oxygen conditions.

When using bench scale measurements, appropriate models can be applied to extend the test results to realistic conditions. For example, fire spread over a horizontal flat combustible slab is modelled by circular spread and burnt-out areas as shown in Figure B.2. The radii of flame spread and burnt-out areas are calculated using Formulae (B.2) and (B.3):

$$r_f = v_f t \tag{B.2}$$
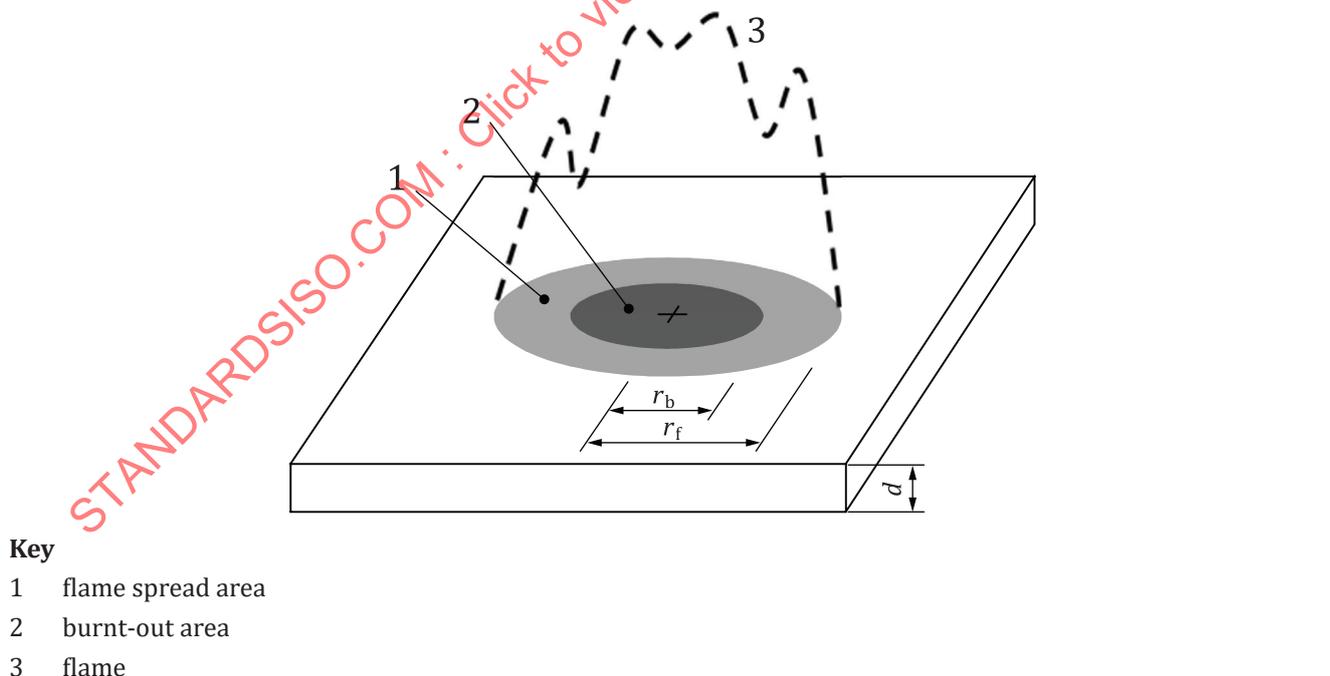
$$r_b = r_f - v_f \frac{\Delta H_c \rho d}{\dot{Q}''} \tag{B.3}$$

The heat release rate and the fire source diameter can be calculated using Formulae (B.4) and (B.5):

$$\dot{Q} = \dot{Q}'' \left(\pi r_f^2 - \pi r_b^2 \right) \tag{B.4}$$

$$D = 2r_f \tag{B.5}$$

The necessary data elements are summarized in Table B.2 in connection with reaction-to-fire test methods.

Key

1 flame spread area
2 burnt-out area
3 flame

Figure B.2 — An example of a model of fire growth over a combustible slab

Table B.2 — Data requirements for calculations

Data element	Description	Units	Source
surface flame spread rate, v_f	movement speed of burning front in a specified direction (horizontal, vertical, lateral)	m/s	Lateral flame spread rate is measured by the ISO 5658-2 LIFT test.
net heat of combustion, ΔH_c	amount of heat generated per unit mass lost by a material under conditions of complete combustion and water in the vapour phase	kJ/kg	ISO 1716 oxygen bomb calorimeter test gives the net heat of combustion under pure oxygen condition. The ISO 5660-1 cone calorimeter test provides heat of combustion (kJ/kg) in a realistic oxygen concentration
heat release rate per unit area, $\dot{Q}''$	heat release rate per unit area of burning	kW/m^2	The ISO 5660-1 cone calorimeter test gives heat release rate per unit area directly.