PD ISO/TS 13447:2013

BSI Standards Publication

Fire safety engineering — Guidance for use of fire zone models

National foreword

This Published Document is the UK implementation of ISO/TS 13447:2013.

The UK participation in its preparation was entrusted to Technical Committee FSH/24, Fire safety engineering.

A list of organizations represented on this committee can be obtained on request to its secretary.

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ISBN 978 0 580 77625 0

ICS 13.220.01

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 August 2013.

Amendments issued since publication

Date	Text affected

PD ISO/TS 13447:2013

TECHNICAL
SPECIFICATION

ISO/TS
13447

First edition
2013-03-15

Fire safety engineering — Guidance for use of fire zone models

Ingénierie de la sécurité incendie — Guide sur l'utilisation de modèles incendie de zone

Reference number
ISO/TS 13447:2013(E)

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Published in Switzerland

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Foreword

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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.

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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/TS 13447 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

This Technical Specification is intended for the use of fire safety practitioners and regulators who use or assess one- or two-zone fire models as part of a fire safety design or analysis. Examples of users include fire safety engineers, authorities having jurisdiction, such as territorial authority officials; and fire service personnel. It is expected that users of this Technical Specification are appropriately qualified and competent in the fields of fire dynamics. It is particularly important that the model users understand the theoretical background and limitations of zone fire models.

In addition to the typical clauses (1, 2, 3 and 4, this Technical Specification includes the following clauses:

— *5: Describes fire zone models in general including underlying principles and assumptions*

— *6: Discusses input parameters and data sources of fire zone models*

— *7: Discusses sensitivity of fire zone models to input variations*

— *8: Gives guidance on use and limitations of fire zone models*

Fire safety engineering — Guidance for use of fire zone models

1 Scope

This Technical Specification provides guidance for assessing the use of fire zone models for calculating gas temperature and concentrations and smoke layer position due to fire within an enclosure. It contains general guidance to be read in conjunction with specific model documentation provided by the model developers. It is not a basis for justifying the use of any particular model.

It is important that users of fire zone models understand the theoretical basis of a model and are capable of assessing the accuracy and validity of the results.

Zone models may also include additional sub-models for predicting related phenomena such as sprinkler, thermal or smoke detector activation, mechanical ventilation, glass fracture or flame spread. A detailed discussion of these related sub models is beyond the scope of this Technical Specification.

NOTE An overview of features covered by various zone models can be found in a survey by Olenick and Carpenter.[1]

This Technical Specification is not intended as a basis for regulation.

2 Normative references

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

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

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

3.1
zone model
calculation model for predicting the environment resulting from a fire in an enclosure where one or more distinct gaseous zones represent layers formed by thermal stratification of buoyant gases

4 Symbols (and abbreviated terms)

$\dot{Q}$ (kW)	Time-dependent rate of heat release
$\dot{m}$ (g/s)	Time-dependent fuel mass loss rate
Δh_c (kJ/g)	Effective heat of combustion

5 General description of fire zone models

5.1 What is a fire zone model?

A fire zone model is a calculation method for predicting the fire effects within an enclosure. The calculations are based on the conservation of mass and energy applied separately to control volumes that subdivide an enclosure into one or more zones. At any instant in time, the properties of each zone are assumed to be uniform. The fire is treated as a source of mass and energy and is a user-prescribed input to the calculation. Figure 1 showing a room elevation illustrates some conceptual features commonly included within a zone model. ISO 16735 gives algebraic formula for calculating specific characteristics of smoke layers generated by fire.[2]

A fire zone model is most commonly a numerical fire model in the form of a computer program but calculations can be done using spreadsheet applications or even by hand. Most commonly used zone models comprise two zones in the form of a hot upper layer and a cooler lower layer. This provides sufficient resolution for many simple pre-flashover fire simulations. However one-zone models have also been developed (e.g. for fully developed postflashover fires) where the assumption of a well-mixed uniform zone is appropriate. Alternatively, fundamental equations for mass and energy conservation can also be extended to more than two zones to provide greater resolution over the height of a compartment.

Multi-room zone models represent a case of multiple interconnected zones where rooms are connected by openings in either the walls or floor/ceiling.

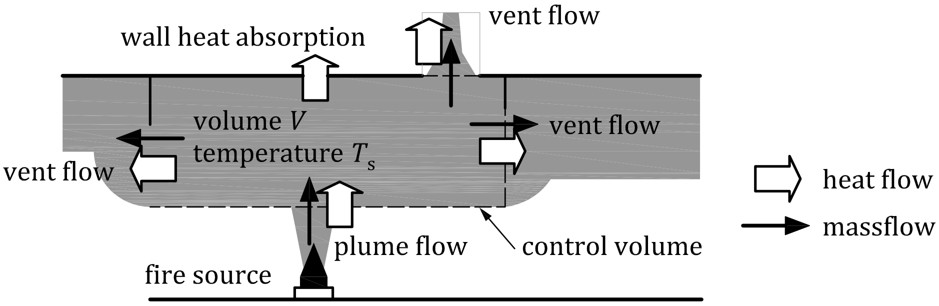

Figure 1 — General heat and mass conservation in an enclosure with a fire source

5.2 Applications

Zone models enable predictions to be made of the smoke temperature, smoke volume (and layer height) and species concentrations within an enclosure resulting from a fire of a given size.

Depending on the level of functionality included within a zone model, typical applications may include:

- predicting the smoke-filling time for a compartment of a given size and for a fire with known time-dependent characteristics ;
- evaluating the life safety tenability of a fire environment for comparison with design criteria ;
- reconstructing a past fire event to support or refute theories about the development of a fire ;
- determining the likely fire size at the time of sprinkler operation and/or the response time of a sprinkler (where a sprinkler response submodel is included) ;
- determining the smoke extract capacity for naturally or mechanically ventilated spaces ;
- determining the impact on important equipment to ensure its continued functionality.

5.3 Advantages

The simplified physics included in zone models mean they are less computationally demanding and are relatively quick to run compared to other state-of-the-art models (e.g. computational fluid dynamics) that attempt to describe the physics using the best available methods. It is an advantage to run a large number of simulations for the same computing resource because it allows the sensitivity of the outputs to the various input parameters to be investigated in greater depth. This is particularly useful for design applications where the exact fire input parameters are not known, yet may have a large influence on the predicted outputs.

The principal advantage of using a computer based zone model over algebraic equations is the flexibility it provides to address some of the transient effects such as heat release, species yields, conduction, automatically opening vents or operating fans based on the fire environment. In addition some zone models offer multi-compartment and /or multi-fire capabilities.

However, use of simplified physics also means zone model simulations may have more limitations in predicting the fire environment than more detailed models for a given scenario. Nonetheless, the accuracy achieved by a zone model can be sufficient for many applications especially where uncertainty in design leads to added conservatism in the selection of model inputs.

5.4 General principles, assumptions and consequences

5.4.1 General

A zone model subdivides a room into one or more control volumes (or zones) with an assumed uniform gas temperature and density throughout the volume. In the simplest case, a single zone model can be used for cases where the fire environment in the room is to be treated as a ‘well stirred reactor’ such as a fully developed post-flashover fire. However, for growing pre-flashover fires, two zones separated by a horizontal layer interface is the most common approach. Models with more than two zones (vertically stacked) have also been developed[3][4] but are less common.

For small compartments of simple geometry, zone models are often assumed to be sufficiently accurate for most situations involving growing pre-flashover room-scale fires. However, this will be dependent on the goals of the analysis. The user needs to consider whether adequate validation has been demonstrated for the selected model in relation to the chosen scenario in the proposed analysis. In subclause 8.8 a more thorough discussion on zone model limitations is available.

5.4.2 Conservation of mass and energy

Fundamental (conservation) equations of energy and mass transport are applied to each control volume. Mass flows enter and leave each control volume via the plume and through openings in the wall or ceiling or via ducts/fans forming part of a mechanical ventilation system. There are also enthalpy flows associated with each mass flow entering and leaving the control volume and heat transfer terms like radiation and reradiation, along with the combustion energy released by the burning fuel. Heat losses by conduction through surfaces or by radiation through openings determine the net heat transferred to or from the control volume and the resultant change in the average temperature of the control volume gases.

The position of the interface between the adjacent zones depends on the volume of each zone relative to the volume of the room. The conservation equations generally solve for the volume and gas temperatures of each zone as well as the room pressure. Many other formulations of the conservation equations may also be used.[5] Most zone models represent each volume as a horizontal layer of gas with a constant cross-section (defined by the area of the room and a height that varies with time). A constant cross-section is not a necessary condition and some models allow for variations such as sloping ceilings. However, most zone models assume the compartment to be a rectangular volume defined by a length, width and height, and since in this case, the cross-sectional area does not change during the calculation this in effect makes the zone model a one-dimensional analysis with properties able to vary only over the height dimension but not across the area of the enclosure.

Zone models do not explicitly solve equations for conservation of momentum. This means that hot gases are assumed to rise and spread instantaneously beneath a ceiling ignoring the finite time needed for the plume and ceiling jet flows to reach the ceiling and to spread to the far reaches of the enclosure. This assumption is usually reasonable for small enclosures, but for large enclosures in practice it may take many 10s of seconds for a flow of gases from the fire to reach the furthest location in the enclosure. Neglecting this effect may be conservative or non-conservative, at least in theory, depending on the design goal. E.g. for the activation time of a detector neglecting the effect would underestimate the detection time and reduce the safety margin between time of evacuation and untenable conditions. However initial conservatism associated with instantaneous spread beneath a ceiling may be reduced or reversed at later times after the hot layer is established with non-uniformities in the position of the smoke layer occurring in compartments of large area due to gravity waves, heat losses, and loss of buoyancy etc.

A two-zone model differentiates the upper and lower layer by a difference in the layer properties (e.g. temperature, density, concentration). Each uniform layer is treated as an ideal gas. An upper layer can exist at any time from the beginning of the calculation and it may or may not be a real smoke layer. A non-smoke upper layer can be developed by ventilation conditions alone wherever there are ambient temperature differences between rooms or from a room to the outside.[6] However, this would usually be of little consequence when evaluating the fire environment for the purpose of determining human survivability.

Variation of air temperature over the height of a compartment under ambient non-fire conditions is generally ignored. In practice, these temperature gradients could lead to early stratification of smoke at some distance below the ceiling which can be important when attempting to model the performance of smoke detection systems. These effects are usually only important earlier in the fire development when the plume flows are relatively weak and the gas temperature rise is modest and again would usually be of little consequence when evaluating the fire environment for human survivability.

5.4.3 Vents

Zone models typically use the Bernoulli equation to relate the pressure and velocity within a flowing stream of (incompressible) fluid allowing the mass flow through a vent opening to be calculated while friction losses are ignored. The mass flow rate of gases through a wall opening is dependent on the hydrostatic pressure profile either side of the opening. A detailed description of the governing algebraic equations is given in ISO 16737.[7]

In large buildings with many hundreds or thousands of compartments and vents, the use of a traditional two zone model becomes impractical, and more efficient network models[8] have been developed that use a simpler lumped-parameter approach to conserve mass, energy and momentum at the vent connections (or ventilation nodes). However further discussion of network models is beyond the scope of this Technical Specification.

5.4.4 Fire growth

Normally zone models do not model the fire growth i.e. the actual rate of heat release from the fire. The user is required to provide either the rate of heat release or the fuel mass pyrolysis rate and heat of combustion. If the zone model also calculates the concentration of oxygen in each layer then the burning rate and corresponding heat release rate may be constrained to a lower level that can be supported by the available oxygen supply. In this case the model may also track unburned fuel as an additional species which may be allowed to burn in other rooms or outside the enclosure provided sufficient oxygen is available at that location.

If there is a considerable amount of unburned fuel in remote spaces from the room of origin this would suggest that the room of origin may be a well stirred condition indicating a one-zone approach is reasonable.

Preflashover fire growth may be simulated based on the characteristics of actual fuel objects (room contents) or by the use of a generic fire growth curve such as a t-squared fire. In the former case, unless the model includes the capability of estimating the ignition and burning of secondary objects, the simulation can only be based on the initial burning object and it will not be possible to evaluate the fire environment beyond the time that more than one object would be involved in practice. In the latter case of a t-squared or similar generic curve describing the rate of heat release, fire growth may be assumed to continue until restricted by the oxygen supply, or until an assumed peak burning rate is reached. If fully developed or post-flashover burning is to be simulated then the selected model shall have been validated for that purpose.

5.4.5 Plumes

ISO 16734[9] describes a set of equations for quasi steady, axisymmetric fire plumes.

The fire is considered as a point source of energy and particulates manifested by a plume that transports mass from the lower to the upper layer through a process called entrainment. The plume volume is assumed to be small in comparison with the volume of the compartment. No mass is transferred across the interface between the layers except via the plume and vent mixing flows. At some stage during the course of a fire, negatively buoyant flows may be generated due to convective cooling of gases in contact with wall surfaces, resulting in mixing of smoke with air contaminating the “smoke-free” layer. Entrainment is calculated using both theory and empirically derived terms. A variation of about 20 % in entrainment may be expected between the empirically derived entrainment coefficients commonly used.[10] It is assumed that the plume is unaffected by ventilation systems or wind as well as any other induced flows (e.g. due to make-up air supplies). If these effects are present the plume can be disturbed or blown over increasing the total amount of air entrained into the plume and leading to an increase in the thickness of the upper layer and corresponding reduction in temperature. In cases where these induced flows are high, smoke-logging of the space may be observed.

6 Input parameters and data sources for zone fire models

6.1 Enclosure geometry

Zone models usually require enclosures to be represented as rectangular volumes with uniform cross-sectional area over their height. Non rectangular spaces can be modelled as an equivalent rectangular volume such that floor area and perimeter length are conserved. This maintains both the volume and surface area to correctly represent heat transfer. It is also required that the height be conserved because the plume entrainment and smoke production calculations are strongly influenced by the vertical distance between the fire and the smoke layer interface.

Some zone models allow for variations in cross section area over the height of an enclosure (e.g. for a sloping ceiling) in the calculation of the upper layer volume and layer height. However, this capability may not be very important in situations where the occupants are located well below the sloping roofline, where the cross-sectional area of the smoke layer interface is the same as the floor area. If however occupants are assumed to be located at elevations nearer the roof, it is important to carefully consider the time history of the smoke layer, particularly in the early stages of fire development.

In cases where a zone model requires the enclosure to be represented by a rectangular volume, a space with a pitched roof shall be represented by an equivalent rectangular volume. The height of the rectangular volume may be equal to the highest level of the roof, and the floor area adjusted such that the overall volume of the enclosure is conserved. Alternatively, where the height of the clear layer is the primary calculation of interest, the average height of the roof may be used and the floor area and perimeter length conserved. The first representation will more closely represent the entrainment rate and the volume/depth of the smoke layer in cases where the fire plume is located beneath the peak of the roof, however the differences in the calculated clear layer height are not great and generally either assumption may be acceptable.

If in practice the plume is horizontally offset from the peak of a sloping roof (see Figure 2), the actual entrainment is expected to be less due to the lower height over which entrainment occurs. In this case, it is usually conservative to locate the plume beneath the highest part of the roof to generate the greater smoke volume and faster smoke-filling rate. Therefore it generally acceptable to ignore the impact of lower offset plumes where conditions within the lower part of the enclosure are the primary concern.

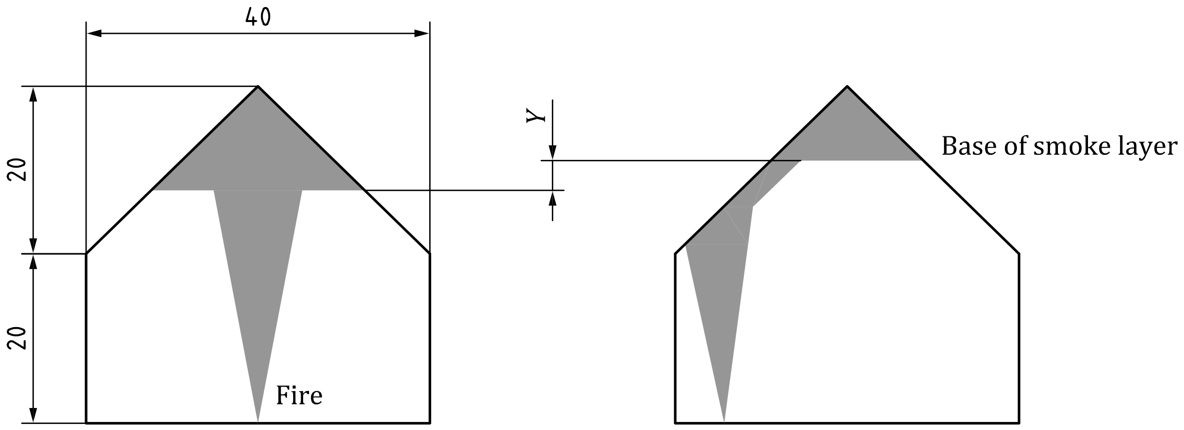

Figure 2 — Example building geometry with the seat of the fire and rising plume centrally (left hand side) and near a wall (right hand side)

Limitations with respect to enclosure size and aspect ratios are discussed in Clause 8.

6.2 Multiple rooms

Zone models may apply to either single rooms or multiple rooms connected to each other and the outside with openings (called vents). Models may be limited in the maximum number of rooms or vents able to be accommodated.

The accuracy of zone model results for adjacent rooms can be expected to decrease with the number of rooms that lie between the room of fire origin and a target room (i.e. in the case of a six room model, more reliable results can be expected where five rooms are directly connected to the room of origin than for the case where all six rooms are connected in series and there are five door openings between the room of fire origin and the target space). Uncertainty in the vent flow calculations will be multiplied with each successive vent flow increasing the total uncertainty. Users should aim to use the simplest arrangement and least number of rooms that can adequately represent the building to be modelled.

6.3 Openings

Openings such as doors and windows may be located within either internal or external walls of the building and these are usually represented as rectangular openings defined by their width, height and elevation in the room. Some zone models may only allow a single opening, while others may permit multiple openings.

A flow coefficient, defined as the ratio of effective flow area over geometrical opening area is typically in the range 0.6 - 0.7 for rectangular orifice-type vents.[11] In practice the flow coefficient depends on the shape, and smoothness of surfaces (e.g. round or sharp edges). In general, flow coefficients vary for different shaped openings e.g. for fins, the flow coefficient can be as low as 0.20; and where the top of a rectangular orifice-type vent opening is at the same elevation and is continuous with the ceiling the flow coefficient may be closer to 1.0.

Some models assume a constant default value for the flow coefficient, in other models it may be adjusted to allow for the individual shape and construction details of the opening. The width of multiple openings in a room may be summed and represented as a single opening when the height and elevation of the openings are the same and they connect to the same space (e.g. outside the building). Some models may also allow the openings to be opened or closed, or the width of an opening to be varied, during a simulation.

In most zone models, room pressure changes need to be small enough that its effect on gas density is negligible. This may be an issue for pressurized spaces and specific approaches may be needed for these cases that are not usually covered by those zone models intended for the built environment. Some specialized models can account for the pressure variations in a confined and ventilated space, e.g. for nuclear plant applications.

Zone models intended for the built environment should not be used for completely air tight spaces, and leakage from the system to the outdoors should be included,[6] or other means provided for addressing the pressure build-up. Compartment leakage may be modelled using a narrow vent spanning from floor to ceiling with the width selected to provide the desired amount of leakage area.

6.4 Bounding materials

Zone models typically assume the bounding materials (e.g. walls, ceiling and floors) to be inert and non-combustible (i.e. they do not ignite and contribute energy to the fire). In this case if combustible materials such as plastics or wood products are used as surface materials on the walls or ceiling, in practice they could be ignited by the fire source and contribute additional fuel and energy to the fire which the zone model would not automatically include in the calculations and hazard predictions. The user should be aware of this, and make the necessary allowances when selecting an appropriate rate of heat release input to calculations. Alternatives could include using multiple fire sources or surface flame spread sub-models, if implemented in the specific model.

Thermal properties of the bounding materials influence the conduction heat losses from the enclosure, and therefore will influence the layer gas temperatures and volumes. Some zone models account for heat losses by using a total heat loss fraction as an input, while other models attempt to calculate the conduction losses using finite difference methods accounting for thermal properties of the bounding materials. Some models may allow bounding surfaces to be constructed from multiple layers and materials, with or without air gaps, or as a single layer only with specified material thermal properties. Some models treat heat transfer to two surfaces only (those in contact with the upper layer gases and those in contact with the lower layer gases), while others calculate the heat transfer to four or more surfaces.

In most zone models, any temperature dependency of the bounding material thermal properties (e.g. thermal conductivity, specific heat) is ignored and constant values are used in calculations. This is considered an acceptable assumption given the overall level of accuracy of the zone model. A lower value of thermal conductivity for the bounding materials will lead to higher predicted exposed surface temperatures and higher room gas temperatures. It is recommended that an average value for the material thermal conductivity over the expected temperature range of interest be used. Input values for thermal properties can be obtained from heat transfer texts, handbooks or product technical literature.

Zone models do not account for any heat transfer to the contents of the room, only heat transfer to the bounding enclosure surfaces, although this is not likely to significantly affect the results obtained.

6.5 Design fire parameters

The design fire is the quantitative description of the fire characteristics to be used by the zone model. The most important input variable influencing the course of the fire and in particular the gas temperatures reached is the rate of the heat release as a function of time.[12] If a zone model is used to assess factors that are dependent on the smoke density such as visibility through smoke or the response of optical smoke detectors, appropriate selection of the smoke/soot yield input parameter is also very important.

Since in most zone models, the design fire characteristics are input variables to be provided by the user, it is critical that for design applications in particular, the project stakeholders and regulators agree beforehand on the design fire to be used including rate of heat release and species production rates. Guidance on selection of design fire scenarios and design fires is given in ISO/TS 16733.[13]

6.5.1 Rate of heat release

Two of the following three fire characteristics are typically required to be specified in a zone model. The variables are related such that

$$\dot{Q} = \dot{m} \Delta h_c$$

where

$\dot{Q}$ (kW)	Time-dependent rate of heat release;
$\dot{m}$ (g/s)	Time-dependent fuel mass loss rate;
Δh_c (kJ/g)	Effective heat of combustion.

6.5.2 Radiant Loss Fraction

The radiant loss fraction, being the proportion of the total combustion energy that is lost by radiation from the plume, may be required with the balance being the convective heat release transported to the layers and used to raise the temperature of the layer gases. Radiative heat transfer strongly affects the development of conditions leading to flashover, including the secondary ignition of materials, and the hot layer depth and gas temperature.

Although the radiant loss fraction in real fires varies with fuel type, temperature, available oxygen and soot concentration in the flame, zone models typically use a constant value. However, the radiant loss fraction may or may not be user input depending on the specific zone model.

The radiant loss fraction can vary in the range 0.15 to 0.50 depending on the fuel with a value of 0.3 considered to be a reasonable default value for sooty fires.[14] Additional data on radiant loss fractions can be found in Reference.[15]

6.5.3 Species production

Some zone models track and calculate the concentration of various combustion products such as carbon monoxide (CO), carbon dioxide (CO_2), smoke/soot (C), hydrogen cyanide (HCN), water vapour (H_2O) and unburned hydrocarbons. Oxygen consumed during the combustion reaction must also be accounted for.

Species production rates input to a zone model may be either expressed as a yield i.e. mass of species produced per unit mass of fuel pyrolysed, or as specific ratios of the yield e.g. C/CO. Specific zone models will require species production rates to be input in a particular format. Species production rates in practice will vary during the course of a fire depending on the fuel composition and the combustion conditions at the time.

It is common for an average species production rate derived from laboratory experiments to be used for input to a zone model.

Calculations of concentrations of asphyxiant gases (e.g for CO, HCN, CO_2) enable a tenability analysis to be carried out for life safety assessments using methodology such as that described in ISO 13571.[16]

Water vapour and carbon dioxide gases along with the presence of soot particles in the hot layer allow a more detailed calculation of the radiation exchange including emission/absorption by the gas layers.

In these cases, the following additional inputs relating to the fire effluents may also be required.

a) Smoke/soot

Smoke and soot particulates are commonly considered to be carbon particles distributed through the gas layers. Model input may be in the form of a yield (mass of carbon per mass of fuel pyrolysed in g/g) or as the mass ratio of C/CO_2.

Reasonable soot yield values for well-ventilated free burning fires involving "sooty" fuels are in the range 0.05 – 0.10 g/g [14][17] with lesser values appropriate for clean burning fuels. These give reasonable results with models that do not account for soot deposition i.e. these are calibrated values and higher numbers may be appropriate if the model also allows for the deposition of soot on surfaces. There are currently no established models that include soot deposition effects.

Significantly higher values of soot yield may be appropriate for underventilated or postflashover conditions as discussed below. Specific products may even cause higher soot yields than mentioned above due to chemistry of the material used e.g. due to chemical treatment or the chemical structure of the fuel (high C/H ratio).

b) Carbon monoxide and carbon dioxide

Carbon monoxide (CO) and carbon dioxide (CO_2) are both products of pyrolysis and combustion. CO is an odourless and colourless gas and its production is primarily dependent on the equivalence ratio and the upper layer temperature. It is not strongly dependent on the fuel type. Well ventilated flaming fires typically generate CO/CO_2 ratios < 0.05.[18]

The influence of CO_2 is mainly its effect on the rate of respiration of other gases, while the oxygen depleted gases have a hypoxic effect. In cases where combustible materials are pyrolysing in a vitiated hot layer (e.g. wood ceilings), there may be large increases in the observed CO yield.

c) Hydrogen cyanide

Hydrogen cyanide can be assumed to be produced by nitrogen containing fuels such as polyurethane foam, wool, nylon, synthetic rubber and melamine. There is very limited data available in the literature on the yields of hydrogen cyanide in fires. Reference[19] describes an investigation of HCN generation from some common nitrogen containing materials in residential environments under both flaming and non-flaming conditions.

d) Under ventilated burning

Under conditions of incomplete combustion where the oxygen supply is restricted the yields of CO and C (soot) will increase while the CO_2 will decrease. The extent to which the combustion is under-ventilated can be expressed in terms of a global equivalence ratio (Φ), where well ventilated conditions correspond to $\Phi < 1$ and under ventilated conditions correspond to $\Phi > 1$. Reference[20] proposes empirical correlations for CO yield as a function of equivalence ratio and temperature based on hexane data as a lower bound.

Some zone models require the input to be adjusted manually during the simulation to account for the burning conditions, while other models may include subroutines that adjust the yield during a simulation based on the conditions. It is important to be aware of these factors because if only yields corresponding to well ventilated flaming combustion are input, and the fire transitions to an under ventilated regime then the predicted values for carbon monoxide concentration and smoke optical density may be significantly under-predicted.

Reasonable carbon monoxide yield values for postflashover under-ventilated fires involving wood products and typical office-type contents are in the range 0.2 – 0.3 g/g.[11] Reasonable carbon dioxide yield values for postflashover under-ventilated fires involving wood products and typical office-type contents are in the range 1.1 – 1.5 g/g.[11] Postflashover CO/CO_2 ratios are typically in the range 0.1 - 0.4.

e) Deposition of combustion products on surfaces

The rate of deposition of combustion products on room surfaces may be of interest for several reasons. For example soot deposition is of interest as it may affect the predicted soot and optical density calculations. The amount of soot deposition will depend on the room surface area to volume ratio, the fuel type, and the location of surfaces relative to the fire. Most commonly it is ignored in zone model calculations with all the soot assumed to be uniformly distributed throughout the gas layers. This is generally a conservative assumption leading to the over-prediction of the soot concentrations.

The deposition of halogen acid gases on surfaces is of interest to understand the risk of damage due to the corrosion. Most zone models do not explicitly evaluate these risks.

f) Sources of data

Sources of data for the yields of fire effluents are discussed in ISO 19706.[21]

The SFPE Handbook of Fire Protection Engineering[15] also provides some data on the generation rate of combustion products.

7 Model sensitivity

ISO 16730 gives detailed guidance on the assessment, verification and validation of calculation methods.[22]

The overall accuracy of zone models is closely tied to the specificity, care and completeness of the data provided.[23]

It is recommended to conduct sensitivity analysis requiring multiple simulations rather than carrying out only a single simulation. Sensitivity refers to the rate of change of the model output with respect to input variations.[23] Model predictions may be sensitive to uncertainties in the input data, the level of rigor employed in modelling the physics and chemistry and the accuracy of the numerical methods. Minor variations in input should not compromise the conclusions of the analysis.

The rate of heat release assumed is often maximised to establish the most severe fire, but this may reduce the fire duration to very short values. These might not be the optimum conditions that impart the greatest harm. Fire severity calculations need to demonstrate acceptable building response to a range of possible fires rather than to a single fire scenario.

It has been reported that gas and surface temperatures, oxygen concentration and compartment pressure show roughly 10 % diversions in response to a 15 % change in heat release rate whereas heat fluxes show roughly 20 % change whereas the height of the gas layer is relatively insensitive to the change in the rate of heat release.[23]

The calculation of the upper layer temperature and layer height has a greater uncertainty in rooms remote from the room of fire origin compared to those in the room of fire origin.[23]

It is advised that calculation time steps of the order of 0.5 – 1.0 s are usually adequate for zone model use.[6]

8 Uses and limitations

8.1 General

For the simulation of a real world situation, the user of a specific fire zone model should consider the effects as described in subclauses 8.2 through 8.10 before using the model.

Next, the model shall be checked to ensure it covers the effects from the real world scenario under consideration. For this purpose subclause 8.10 provides a checklist that may help in comparing whether these effects may apply. If the model under consideration does not account for these effects, it is up to the user of the model to judge whether another model needs to be applied instead, or if the effect is unimportant under the prevailing conditions.

8.2 Localized effects

Zone models do not consider localized heating effects (other than treatment of specific phenomena such as the ceiling jet). An analysis that only uses the model prediction of the average hot layer may not be correct in predicting localized phenomena.

When interpreting model results, it is necessary to be aware of the following:

- Average hot layer temperatures cannot be used to assess the risk of ignition of combustible materials in contact with the upper layer (e.g. walls and ceiling). The incident heat flux due to sustained flame contact with combustible materials is many times higher than that due to the average temperature of the hot layer. (A ceiling jet temperature calculation may provide a better indicator.) Some models include an estimation of the impact of the plume on target temperatures for heat transfer calculations, including temperature estimates from the flaming region.
- Fans used for mechanical extraction may be exposed to localized heating from the plume or ceiling jets that might exceed the rated temperature of the fan.
- Zone models are not suitable for a detailed study of flows within a compartment such as may be needed for fire detector siting.[23] In practice this can be affected by vent locations and flows.

8.3 Compartment effects

Most models ignore enhancement to the burning rate caused by increased radiation to the fuel surfaces due to radiative feedback from the hot gas layer or compartment surfaces. If using free-burning or furniture calorimeter data to describe the rate of heat release, the user may need to separately account for compartment effects in the design fire.[24]

Enhancement of the mass pyrolysis rate has been shown experimentally to be as much as twice the ventilation limit for pool fires and 1,3 times the ventilation limit for wood cribs.[25] These effects will be more important in small rooms and as the fire development approaches flashover.

A crucial factor influencing the degree of radiant feedback is the size of the self-view factor. A mattress has zero (no part of its top surface sees any other part of the mattress), thus for mattresses the radiative feedback effect from the smoke layer is very high, so that when located inside a room the heat release rate may be increased by a factor of three or more, compared to open burn testing. For upholstered furniture such as a chair with a high self-view factor, the effect, by contrast is typically only 1,25 or less. In addition, for many foams up to 50 % of the heat release comes from liquefied material that drops down and burns on the floor. For such shielded pools, they see practically nothing of the radiation from the upper portions of the compartment.

Zone models have a tendency to show the position of the layer height rising as the heat release decays which is consistent with the upper layer reducing in volume as its temperature cools, however, this behaviour is generally not exhibited in experiments[26] and therefore may not occur in practice. Nonetheless, this effect need only be considered if the decay stage of the fire is relevant to the analysis.

8.4 Plumes

Plume entrainment is the principal means of transporting gases from the lower to upper layer and zone models commonly adopt empirical approaches to estimate the amount of air entrained into the fire plume. There have been a number of different equations proposed in the literature based on pool fires and axisymmetric gas burners as well as theoretical models.

The different entrainment models can lead to a factor of two variation in the results for layer height and gas temperature and entrainment rate.[27][28]

The Morton-Turner-Taylor theory suggests that entrainment in the buoyant plume region should depend on $H^{5/3}$, whereas the McCaffrey correlations uses the 1.895 power for the buoyant plume. According to Rockett,[29] the McCaffrey correlations result in a severe over-prediction of plume flows far above the fire (i.e. in tall spaces) but provides good predictions in immediate over-fire region more relevant for small rooms. Over estimating the entrainment will result in upper layers that are deeper and cooler than otherwise expected. This could have a large impact with added cost implications if used to size a smoke extract system based on raising the layer height. It is therefore necessary to check that the plume equation used in the zone model is appropriate for the scale or height of the enclosure being modelled. This effect is demonstrated in Figure 3 with two different plume correlations for the buoyant plume as an example. Heskestad's plume depends on location of virtual origin, which is in turn dependent on fire source diameter.

Entrainment coefficients are usually derived from measurements in calm environments. The actual plume flow may be significantly greater in disturbed environments (e.g. due to HVAC or door/window flows).[6] Ventilation conditions can also affect plume entrainment including make-up air flows in atrium smoke management systems.[30]

When the fire plume is very close to a wall or room corner, plume entrainment is reduced when compared to an axisymmetric plume and some models account for this by modifying the entrainment coefficient. In a narrow tall enclosure (e.g. shafts) a fire plume may intersect with the wall before reaching the ceiling reducing the total amount of entrainment but also lessening the likelihood of a two-layer environment forming. Some zone models include sub-models to specifically address these phenomena.

Plume entrainment correlations are also commonly adapted to describe the entrainment into a vent flow as it rises from an opening to the ceiling in an adjacent room. In these cases, vent plumes are commonly treated as axisymmetric plumes with a virtual origin located to produce the same mass and energy fluxes as the actual vent plume.[31]

Entrainment correlations have typically been derived from pool fires or gas burners whose entrainment characteristics may differ from real items of furniture and this introduces an additional source of error when applied to typical building contents. In this case, if the entrainment is overestimated the layer will drop more quickly, and be cooler and vice versa.

Entrainment in a spill plume may be larger than the entrainment in the axisymmetric plume, and this would not be accounted for by most simple zone models – more specialized models to account for these effects would be needed.

Entrainment calculations in zone models also do not generally account for any interaction effects following the activation of water or gaseous extinguishing systems that may contribute to cooling or turbulence in the smoke layer and general smoke-logging effects within the enclosure.

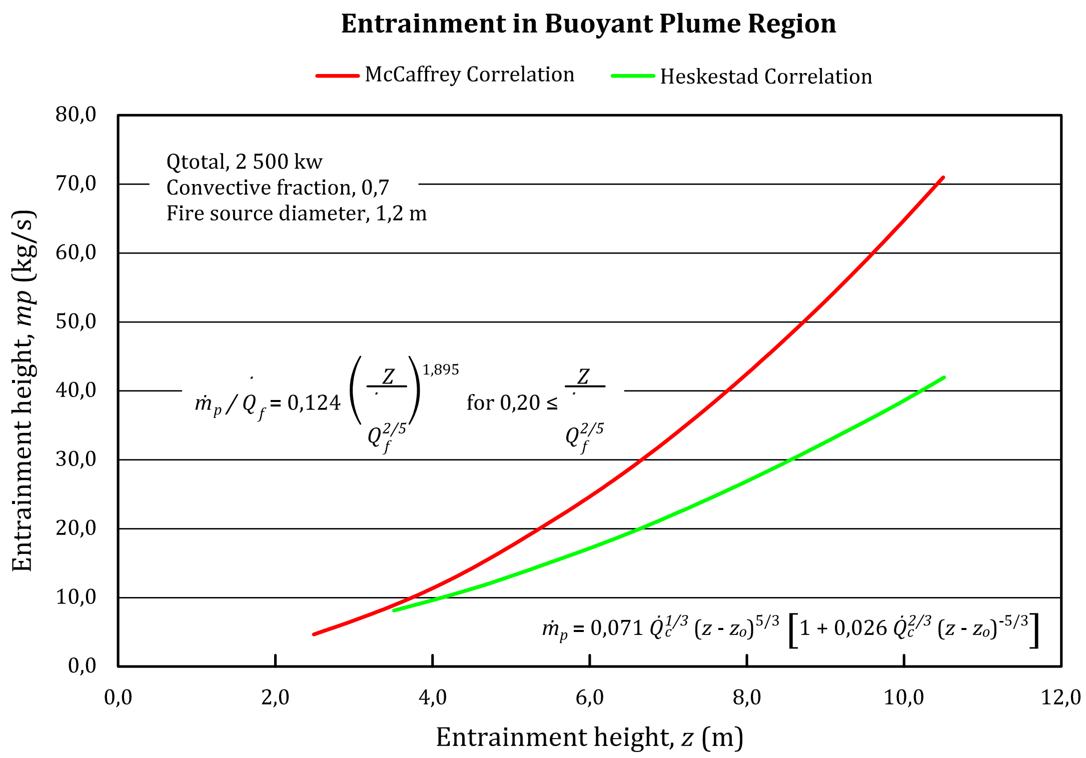

Figure 3 — Comparison of plume entrainment correlations for 2500 kW fire

8.5 Ceiling vents

Smoke flow through ceiling openings occurs when there is a pressure difference across the opening. In most cases the flow is driven by the hydrostatic pressure difference from the high pressure to the low pressure side. The pressure is generated by the buoyancy of a hot smoke layer beneath the ceiling. In this case, a traditional orifice-type calculation of the flow can be done. Typically flow coefficients corresponding to a sharp edged circular orifice would be used.

In some cases buoyancy instability may be present which can significantly affect the validity and accuracy of using the standard Bernoulli flow model. This occurs when there is a relatively heavy, cool fluid (e.g. ambient exterior air) positioned directly above a ceiling vent with a low density hot smoke layer below the vent. This is an unstable arrangement and can result in an “exchange-type” flow where some of the dense, cool exterior air will flow downwards through the vent into the fire enclosure.[32] Some zone models include both the pressure-driven and the exchange-type flows while others may not.

This type of vent flow model is not suitable for large floor openings of the type found in malls and atria where there is limited ceiling area to contain a hot gas layer below the vent opening and generate the buoyancy forces. In these cases, a fire plume located directly below the opening will result in a plume flow directly into the upper level and if located in an adjacent space instead, there may be balcony spill plumes generated increasing the plume flow into the upper level. These phenomena are quite different to that represented by the standard ceiling vent vertical-flow model. An atrium-type space can be better modelled as a large vertical space with compartments connected at various levels.

Wind effects on the vent flow are commonly ignored but could be important in some cases.

8.6 Stratification

If ambient conditions are not uniform within the enclosure e.g. where the air temperature is higher directly beneath an uninsulated roof, there may be some layer stratification effects early in the fire development which could be important when considering the response of smoke detectors. As the fire develops and rate of heat release and gas temperatures increase, these stratification effects will become less important. Typically zone models do not allow for these effects.

8.7 Plug-holing

The phenomenon of plug-holing occurs when the rate of volumetric flow through a ceiling vent is large enough to cause a local depression in the smoke layer depth that is comparable to the average depth of the layer. This results in some of the fluid from the lower layer being included in the extracted gases with the balance from the upper layer. A zone model that does not take this effect into account will overestimate the efficiency of the venting system by removing more of the hot layer gases than might actually occur. This phenomenon applies to both natural venting and mechanical ventilation systems.

Plug-holing can be predicted on the basis of the Froude number and the layer thickness. The literature indicates that for circular vents a Froude number greater than 1,6 will result in plug-holing.[33][34] For natural venting, to avoid plug-holing each ceiling vent should have an area less than $2(H - z)^2$ where H-z is the depth of the hot layer.[11]

Some zone models include these plug-holing effects.

8.8 Enclosure sizes, dimensions, geometry

Caution is needed for enclosures with aspect ratios larger than about 5 since zone models may not be appropriate for long hallways ($L/W > 5$) or tall shafts ($H/\min(L,W) > 5$).[23] A particular model should be examined to see if it provides a means of modelling these cases.

Caution should be exercised with large fires in low-ceiling height spaces, where the flames reach the ceiling and spread beneath it. A zone model may ignore the presence of flames across the ceiling and overestimate the heat losses from the hot layer to the ceiling resulting in cooler and thinner layer depth predictions.[11]

Consider the extent to which large obstructions at ceiling level will influence the results. Geometrically complex enclosures with complicated ceiling shapes may not be suitable for analysis using zone models and alternative methods of analysis should be employed. Most zone models require enclosures to be represented as rectangular volumes.

Since zone models assume the formation of a uniformly stratified upper layer, a small fire in a large space may not meet this requirement. A small fire in a large space will not be able to drive the fire gases to the ceiling and smoke may stratify at some intermediate height rendering ceiling ventilation ineffective.[23] Some researchers have suggested a minimum fire size of 0.1 kW per m^3 of compartment volume as a guide for ensuring the establishment of a hot layer.[35]

At the other extreme the ratio of heat release to compartment volume should not exceed about 1MW/m^3 due to limitations on the numerical routines.[23] The two-layer assumption is however likely to break down well before this limit is reached.

Smoke baffles or screens may be employed in larger spaces to create smoke reservoirs with volumes that increase the effectiveness of smoke removal applications. This approach also increases the suitability of using a zone model in the analysis.

The assumption of uniform properties within a layer may be challenged for spaces that are very long or wide due to cooling and loss of buoyancy far from the fire that may not be accounted for in the zone model. In order to extend the applicability of zone models for larger spaces, users have sometimes subdivided single large enclosures into a number of small “virtual” or “pseudo” rooms connected by full height and width openings in order to better simulate variations in gas temperature and layer height across the area of a large space, without the computational expense of applying a more sophisticated CFD method. Several researchers have discussed this approach in the literature.[36][37][38][39] From the literature cited above it follows that special caution is needed when applying this approach due to the additional consideration of matters such as the opening flow coefficients for the internal openings.[6] A pseudo room approach is best used as part of a sensitivity analysis including assessing the affect of the number of rooms and the pseudo vent height selected.[38]

8.9 Postflashover Fires

Many zone models are not suitable for modelling postflashover fires because they do not include specific submodels for the mass pyrolysis rate of the fuel after flashover. In particular the effect of ventilation limited burning on the mass pyrolysis must be appropriately modelled. If the user has supplied the rate of heat release versus time as well as the heat of combustion as input, the zone model will calculate the mass loss rate by dividing the former by the latter. This assumed linear proportionality between the heat release rate and the mass loss may be incorrect for under ventilated and oxygen constrained burning environments, but can usually be ignored for well ventilated preflashover fires.

The heat release rate specification provided as input to a zone model commonly corresponds to a single item of furniture, or a continuously growing fire (e.g. t-squared fire). However, in the former case, as the fire develops and conditions within the room approach flashover, the actual heat release rate from the fire may differ from the input fire specification due to fire spreading to other combustible materials or secondary items nearby. An increasing level of radiant feedback from the hot layer may cause an increase in the pyrolysis and burning rate of the fuel. It is difficult for the user to anticipate the timing and magnitude of these effects in advance, and they are usually allowed for by using a conservative approach to selecting the design fire characteristics.

Under fully developed fire conditions, the heat loss by radiation through openings can be significant and should preferably be accounted for in zone models intended for postflashover applications.

The user should be aware of conditions corresponding to the onset of flashover in order to terminate zone model simulations or discard results where the zone model used was not intended for postflashover applications.

8.10 Comparison of real world effects and model capabilities

As stated in subclause 8.1, an example checklist is presented here to assist the user in deciding whether a model intended for predictions of real world behaviour meets the requirements imposed from effects described in subclauses 8.2 through 8.10.

Depending on the purpose of the simulation, one or more of the effects described in subclauses 8.2 through 8.9 may not be relevant for a given specific real world scenario. In some cases, if the effect is considered to be small enough, it may be compensated for by selecting more conservative values for other input parameters. In other cases, the user may have no choice but to select a different fire model entirely. The following checklist is intended to be illustrative only and should not be regarded as comprehensive.

Table 1

Effect	Specific condition in the real world scenario	Is the effect within the scope of the intended fire zone model?	What to do when the specific effect is not covered?
Localised effects	e.g. influence of the ceiling jet on fire detection devices	Does the fire model include ceiling jet effects?	If ceiling jet is not modelled then choose another model that includes the ceiling jet.
Compartment effects	e.g. influence of radiant feedback on the burning rate of fuel	Does the fire model account for radiant feedback effects?	If not provided for, make allowance for these effects when specifying the input rate of heat release.
Plumes	e.g. balcony spill plume	Does the fire model include balcony spill plume effects?	If the scenario requires consideration of balcony spill plume effects not included in the zone model, then elect to use a CFD model or spill plume correlations developed for the purpose.
Ceiling vents	e.g. vertical vent flow through a ceiling or roof vent	Does the fire model predict flow through a ceiling/roof vent?	If ceiling vents are not modelled, approximate using a shallow wall vent at high level located beneath the ceiling.
Stratification	e.g. stratification of smoke layer due to uninsulated roof	Will stratification effects at an early stage of fire development affect the fire safety goal?	Consider whether stratification occurs at a time when conditions are hazardous to occupants. If not, then can ignore.
Plug-holing	e.g. extracting smoke from a ceiling reservoir using mechanical fans	Does the fire model calculate plug-holing effects and adjust the calculation of mass flow accordingly?	If plug-holing is not modelled, check Froude Number and design to avoid occurrence of plug-holing.
Enclosure size, dimensions and geometry	e.g. the enclosure has a sloping ceiling	Does the fire model require the enclosure to have a flat ceiling?	If building occupants are only to be found below the level of the sloping ceiling, this effect can be ignored and the average height used in the model.
Post flashover fire	e.g. post flashover burning	Does the fire model adequately address changes in pyrolysis and burning rates under fully developed and under-ventilated fire conditions?	If no, then simulation will only be valid for growing well ventilated fires.

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