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Performance criteria used in fire safety design

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Abstract

In many countries around the world, building codes are shifting from prescriptive- to performance-based for technical, economic, and social reasons. This move is made possible by progress in fire safety technologies, including the development of engineering tools that are required to implement performance codes. The development of performance-based codes follows a transparent, hierarchical structure in which there are usually three levels of objectives. The top level objectives usually state the functional requirements and the lowest level the performance criteria. Usually, one middle level exists, however, more levels can be used in this hierarchical structure depending on the complexity of the requirements. The success of performance-based codes depends on the ability to establish performance criteria that will be verifiable and enforceable. The performance criteria should be such that designers can easily demonstrate, using engineering tools, that their designs meet them and that the code authority can enforce them. This paper presents the performance criteria that are currently used by fire protection engineers in designing fire safety systems in buildings. These include deterministic and probabilistic design criteria as well as safety factors. The deterministic criteria relate mainly to life safety levels, fire growth and spread levels, fire exposure and structural performance. The probabilistic criteria focus on the incident severity and incident likelihood. Finally, the inclusion of safety factors permits a conservative design and allows for a smaller margin of error due to uncertainty in the models and the input data.

Keywords: Performance criteria; Fire safety; Building codes

1. Introduction

Building codes may be classified as prescriptive- or performance-based. In prescriptive codes, most requirements prescribe the solutions without explicitly stating their intent. In performance codes, however, desired objectives are presented and the designers are given the freedom to choose a solution that will meet the objectives.

Currently, in most countries around the world, prescriptive codes are used as the primary means of fire safety design. Many of these codes have become complex and unduly restrictive because of the constant imposing of new requirements in addition to the existing ones. As a result of this and advances in fire safety engineering, many countries are moving towards the adoption of performance-based codes. The move can also be justified by examining Table 1 which summarizes the advantages and disadvantages of both prescriptive- and performance-based codes.

The adoption of performance-based codes requires the development of performance fire safety engineering criteria to support these regulations in terms of assessing the acceptability of solutions against the established objectives. An extensive literature survey conducted by Hadjisophocleous et al.

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Table 1
Prescription vs. performance

Code type	Advantages	Disadvantages
Prescriptive codes	● Straightforward evaluation of compliance with established requirements ● No requirements for high level of engineering expertise	● Requirements specified without statement of objectives ● Complexity of the structure of existing codes ● No promotion of cost-effective designs ● Very little flexibility for innovation ● Presumption that there is only one way of providing the level of safety
Performance codes	● Establishment of clear safety goals and leaving the means of achieving those goals to the designer ● Permitting innovative design solutions that meet the performance requirements ● Eliminating technical barriers to trade for a smooth flow of products ● Harmonization of international regulation systems ● Facilitating use of new knowledge when available ● Allowance for cost-effectiveness and flexibility in design ● Non-complex documents ● Permitting the prompt introduction of new technologies to the market place	● Difficult to define quantitative levels of safety (performance criteria) ● Need for education because of lack of understanding especially during first stages of application ● Difficult to evaluate compliance with established requirements ● Need for validation of the tools used for quantification

[13] indicates that a number of criteria, deterministic and probabilistic, that can be used in a performance-based code environment, are already present in today's prescriptive code environment. Most prescriptive codes allow for alternative designs, as long as the safety levels they provide are equivalent to those intended by the code. Because of this equivalency clause, a number of building designs are currently based on engineering calculations rather than following the prescriptions of the code. The results of the calculations are then evaluated, using performance criteria, to determine whether the fire safety level, as intended by the code, is achieved.

This paper presents and discusses a representative sample of performance criteria and safety factors in use today to demonstrate that, for many aspects of fire safety design, a performance-based approach, through engineering calculations, is already being used. The paper also shows that, although there are still inconsistencies in these performance criteria, their development and use in a performance-based code environment will result in more efficient and effective designs.

2. Performance design criteria

The design of fire protection systems in buildings, using engineering calculations, can be accomplished following deterministic or probabilistic techniques, or both. Usually, deterministic methods are used for calculating fire growth, smoke spread, structural behaviour and occupant evacuation. The results of these calculations are then compared to established deterministic criteria to determine whether the design is acceptable. When probabilistic methods are used, the end result is presented in terms of life or property risk levels for the whole building. In this case, the performance criteria are also given in terms of acceptable risk levels, which are referred to as probabilistic criteria. It should be mentioned that, currently, deterministic criteria are the more commonly used of the two.

2.1. Deterministic criteria

Deterministic calculations provide a quantification of fire processes such as fire growth, fire and smoke spread, evacuation time, structural response and of the consequences of these processes on the building and its occupants. The results of these calculations are then compared to established deterministic criteria to evaluate whether or not the design is satisfactory. For most designs, these criteria have to be met under probable worst-case scenarios. The deterministic criteria presented in this paper relate to fire ignition, fire growth, flashover and post-flashover (fully-developed) fires, as well as to tenability limits for the safety of building occupants.

2.1.1. Fire ignition criteria

To minimize ignition, the radiant heat flux required to ignite a material is usually used as the criterion with thresholds established for various materials. Table 2 illustrates the threshold values proposed for both radiant heat flux and surface temperature for ignition of some materials as identified by the British Standards Institute (BSI) Draft Code of Practice [2].

Table 2
Threshold values for ignition [2]

Material	Radiant heat flux for ignition (kW/m^2)		Surface temperature for ignition (°C)	
	Pilot	Spontaneous	Pilot	Spontaneous
Wood	12	28	350	600
Chipboard	18			
Hardboard	27			
PMMA (Perspex)	21		270	
Flexible PU	16		270	
Polyoxymethylene	17			
Polymethylene	12			
Polyethylene/42% Cl	22			

Table 3
Heat flux range for ignitability [5]

Ignitability	Heat flux range (nominal value) (kW/m^2)
Easy (thin curtains)	≤ 14.1 (10)
Normal (upholstered furniture)	14.1–28.3 (20)
Hard (thick wood)	> 28.3 (40)

The National Fire Protection Research Foundation (NFPRF) Fire Risk Assessment Method (FRAM) [5] classified product ignitability in terms of the heat flux range shown in Table 3.

The data shown in Tables 2 and 3 may be used to determine the ignition of the first item and subsequent items close by. Therefore, one way to minimize ignition is to ensure that the heat sources that may be present in a compartment cannot radiate enough heat to cause ignition of the combustible materials in that compartment.

2.1.2. *Pre-flashover—fire growth criteria*

Following ignition, the rate of fire growth is one of the most important parameters used to determine the performance of a fire safety design. The rate of fire growth can be determined using experimental results, computer models or empirical correlations. One of the most commonly used methods is the t-squared (t^2) fires method in which the heat release rate, Q, is assumed to continuously grow quadratically as a function of time, t, until either the fuel is totally consumed or the heat release rate is assumed to have reached a peak value. In formula form, the fire growth rate curve can be written as:

$$Q = (t/k)^2. \tag{1}$$

Depending on the fuel in-place, the fire may have a growth rate that is either slow, medium, fast, or ultra fast. Table 4 gives the values of the fire growth parameter, k, corresponding to each of the four fire growth rates mentioned above. The fire will continue to grow with time until its heat release rate reaches a maximum level which is governed by both the area of the fuel and the ventilation conditions. For design purposes, the maximum heat release rates per unit fuel area may be obtained from available experimental data. In the absence of such data, the maximum heat release rates listed in Table 5 can be used for design purposes. These values are reported in the BSI Standards [2] for typical occupancies.

Due to the random nature of fire, many different fire scenarios may occur in a building. Bukowski and Babrauskas [4] recommended using the NFPRF FRAM [5] for identifying probabilities of occurrences of such scenarios. In addition, various papers, including the BSI Draft Code of Practice [2], and the New Zealand Design Guide [3], suggest defining standard fire scenarios in the occupancy, referred to as design fires. The design fires are defined by the fuel load per unit area [7], the peak heat release rate and the fire growth rate.

2.1.3. *Post-flashover—fire resistance and spread criteria*

As the fire continues to grow, the temperature in the compartment of fire origin increases and every

Table 4
Typical fire growth parameters [3]

Fire growth rate	k ($s/MW^{1/2}$)	Typical equivalent or real fire
Slow	600	Solid wooden material with a horizontal orientation such as floors
Medium	300	Solid wooden furniture, i.e., desks, cotton/polyester mattresses
Fast	150	Light wooden furniture, i.e., plywood wardrobes, full mail bags
Ultra fast	75	Upholstered chairs, methyl alcohol pool fire

Table 5
Design fire growth rates and maximum heat release rates [2]

Occupancy type	Fire growth rate	Maximum heat realease rate
Office	Medium	250 (kW/m^2)
Retail	Fast	500 (kW/m^2)

part of that compartment is exposed to flame radiation that leads to an event called flashover. Flashover is characterized by the rapid transition from a localized fire to combustion of all exposed fuel surfaces within a compartment. The undesirability of the flashover event makes it important to know its likelihood and timing. The criteria governing the occurrence of flashover are two: the temperature of the upper hot gas layer has reached 600°C or the radiation at the floor has reached 20 kW/m^2.

Fires continuing beyond flashover are referred to as fully-developed fires and are characterized by very high temperatures and heat release rates. This stage is important to consider because it often relates to satisfying the objective of property protection which includes the assurance of barrier fire resistance and the avoidance of fire spread and exposure to immediate areas and adjacent properties. The criteria governing barrier fire resistance and external fire spread and exposure are presented below.

2.1.3.1. Barrier and structural fire resistance. An important element of fire safety design is predicting the failure of a building element due to a fire attack. Building elements can be structural, such as beams, columns and load-bearing walls, or non-structural, such as internal partitions and some external walls. Failure of a structural building element may lead to building collapse, while failure of non-structural building elements (barriers) may lead to fire spread from the compartment of fire origin to other building areas. The objective of fire resistance of a building element is to maintain the load-bearing capacity of the structure, to avoid spread of fire outside the area of fire origin and especially to areas of refuge, and to protect firefighters. Building element fire resistance criteria can be set in terms of stability, integrity and thermal insulation. The New Zealand Design Guide (Buchanan, [3]) lists the relevant failure criteria for different building elements as illustrated in Table 6.

Table 6
Failure criteria for elements of building construction [3]

Building element	Stability	Integrity	Insulation
Partition		x	x
Load bearing wall	x	x	x
Floor/ceiling	x	x	x
Beam or column	x		
Fire resistant glazing		x	

The fire resistance rating of building elements is the common reference performance criterion used for fire barriers. The rating is dependent on the threshold values of surface temperature, plastic deformation, allowable stresses, and ruptures. These threshold values are attained under critical conditions of fire duration and severity. The equivalent fire severity (time) for barrier failure, is dependent on the fire load, building geometry and ventilation characteristics. BSI Standards [2] presents a simple method for determining an element structural failure as follows:

$$L_{crit} \geq \lambda_{str} L \qquad (2)$$

Where

L_{crit} = critical fire load to cause failure

L = design fire load [7]

λ_{str} = design factor ranging between 1.0 and 1.5.

In addition, the threshold values, listed by CIB W14 [7] to describe the criteria for thermal insulation of a separating structure or structural member, are 200°C average temperature on the unexposed side of the separating structure or a maximum temperature of 240°C. Buchanan [3] suggested using an average value of 140°C and a maximum value of 180°C. The values suggested by Buchanan [3] are also the standard test criteria in the CAN/ULC-S101-M89 [6]. Furthermore, O'Hara [18] suggested, as property pro-

Table 7
Critical values of received radiation I_{RC} as listed in Ref. [3]

Condition of neighbour's wall	I_{RC} (kW/m^2)
● Plastic combustible	10
● Cellulosic combustible	12.5
Non-combustible with non-fire resistant glazing	20.0
Non-combustible with fitted fire resistant glazing	50.0

Table 8
Critical values of received radiation I_{RC} as listed in Ref. [19]

I_{RC} (kW/m^2)	Outcome
> 9	Breakage of ordinary glass Ignition of fabrics if in contact with sparks or embers
≥ 21	Ignition of timber if in contact with sparks or embers
≥ 42	Spontaneous ignition of timber

tection criteria, confining thermal damage to 100 m^2 in the area of fire origin with no primary structural member collapsing, and confining non-thermal damage, from smoke and water, to the floor (storey) of fire origin. For a steel roof structure, O'Hara proposed maintaining structural steel temperatures to less than 538°C.

2.1.3.2. External fire spread. Potential fire spread to neighbouring properties can be evaluated based on the critical values of received radiation I_{RC} by these properties. Tables 7 and 8 list these criteria for different building materials.

With the criteria in Tables 7 and 8, it is possible for the designer to calculate the minimum distance between two walls to avoid spread of fire to neighbouring properties.

Other researchers have also described typical threshold values for the critical radiation level at exposed structures from a neighbouring fire as a safety criterion:

- Scherfig [20] used 15 kW/m^2 as the acceptable threshold level for preventing spread from one structure to other exposed structures.
- Barnett and Simpson [1] defined a threshold level as 10 kW/m^2 for plastic cladding, 12.5 kW/m^2 for timber cladding, and 25 kW/m^2 for spontaneous ignition of items just inside the neighbour's windows of the exposed building.

Another aspect of external fire spread and exposure is the formation of openings in the walls of the compartment of fire origin. The designer must consider all possible openings that could be created as the fire develops. Indeed, the creation of openings should be considered in the design because it changes the development of the fire; e.g., a change in ventilation inside the compartment. Openings can be in the form of holes in the barriers or glass breakage. The following criteria can be used to define glass breakage:

- Kim and Taber [15] stated that breakage temperatures on the exposed side of glazing were 150 to 175°C for plain glass and 350°C for both heat strengthened and tempered glass.
- Quaglia [19] related the criteria for breakage of interior ordinary glass as being a temperature of 100°C and, for tempered glass, a temperature of 270°C, while Frantzich et al. [12] used a single value of 300°C.

2.1.4. Life safety criteria

The most important objective in fire safety design is the life safety of occupants. The designer must ensure that the occupants have sufficient time to reach, without harm, a safe refuge area. Deterministic models are usually used to calculate the conditions in a compartment during the fire growth state or the pre-flashover stage. These conditions are criti-

Table 9
Tenability criteria [3]

Tenability type	Tenability limit
Convective heat	Temperature of the gas layer ≤ 65°C (time to incapacitation for 30 min exposure)
Smoke obscuration	Visibility in the relevant layer should not fall below 2 m (optical density 0.5 m^{-1})
Toxicity	$CO \leq 1400$ ppm (small children incapacitated in half the time) $HCN \leq 80$ ppm $O_2 \geq 12\%$ $CO_2 \leq 5\%$ (the above critical values leading to incapacitation in approximately 30 min)
Radiative heat	Radiant flux from upper layer ≤ 2.5 kW/m^2 (this corresponds to an upper gas layer temperature of approximately 200°C. Above this, the tolerance time is less than 20 s)

Table 10
Tenability limit conditions caused by toxic combustion products [2]

Chemical products	5 min exposure		30 min exposure	
	Incapacitation	Death	Incapacitation	Death
Carbon monoxide	6000 ppm	12000 ppm	1400 ppm	2500 ppm
Low oxygen	< 13%	< 5%	< 12%	< 7%
Carbon dioxide	> 7%	> 10%	> 6%	> 9%

cal to determining whether occupants can escape before untenable conditions are reached. The performance criteria for life safety relate to the carbon monoxide (CO), hydrogen cyanide (HCN), oxygen (O_2), carbon dioxide (CO_2), heat flux, air temperature and smoke obscuration levels. These criteria are detailed by DiNenno in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering [9]. The Fire Engineering Design Guide [3] in New Zealand adopted the criteria shown in Table 9 which are, in turn, based on the SFPE Handbook [9].

The BSI Draft Code [2] adopted the limiting conditions for tenability caused by toxic products of combustion, smoke obscuration, and heat illustrated in Tables 10–12 below. These limits are also based on values reported in the SFPE Handbook [9].

In means of escape, Malhotra [17] cited the critical times shown in Table 13 for reaching untenable conditions. As seen in Table 13, with increased protection, the time available to the occupants for evacuation, before untenable conditions are reached, increases.

In addition to the criteria presented above, a variety of other researchers proposed threshold levels for life safety criteria. These levels are case specific and should not be generalized. The following are sample descriptions:

- O'Hara [18] gave a full outline of the performance objectives for a low-risk, low-rise office building. For life safety, the author suggested that, in egress routes, the limiting CO concentration be less than or equal to 1700 ppm and O_2 levels be greater than 15%. For the smoke control system, O'Hara set the performance criteria as keeping the toxic fire product layer at not less than 3 m above the floor. For the means of egress, O'Hara set as a criterion, an evacuation time of 6 min or less.
- Frantzich et al. [12] suggested using 10% as the critical O_2 level for life-safety in a building.
- Scherfig [20] defined the safety criteria for evacuation in terms of visibility thresholds. The author proposes a rule that persons during egress must have a visibility of at least 3 m in the primary fire compartment and 10 m in escape routes.
- Johnson and Timms [14] suggested that the life safety criteria in a shopping mall atrium were to limit the hot layer to not less than 1.9 m from the floor and to limit the hot layer temperature to not more than 183°C.

2.1.5. Safety factors

Safety factors have been used in most engineering designs to account for uncertainties in calculations. Safety factors are also used in fire safety engineering

Table 11
Limiting conditions for tenability caused by smoke obscuration [2]

Location	Minimum visibility within room
In a small room	2 m
Other rooms	10 m

Table 12
Limiting conditions for tenability caused by heat [2]

Mode of heat transfer	Symptom	Exposure level
Radiation	Severe skin pain	2.5 (kW/m^2)
Conduction	Skin burns 1 s of contact (metal)	60°C
Convection	Skin/lungs affected by hot gas in > 60 s	120°C
Convection	Skin/lungs affected by hot gas in < 60 s	190°C

Table 13
Critical times for reaching untenable conditions [17]

Type of zone	Critical time to reach untenable conditions in means of escape (min)
Unprotected fire zone (zone of occurrence of fire)	
● Normal sized room (≤ 100 m^2)	2–2.5
● Larger compartments or room (height > 4 m)	4–6
Partially protected zone (zone with heat and smoke resisting barriers for a limited time)	
● Natural smoke expulsion	5
● Pressurization or extraction system	10
Fully protected zone (zone where protection remains acceptable for the whole duration for which protection is required in the building)	
● Natural smoke expulsion, no lobby	30
● Natural smoke expulsion, lobby	45
● Pressurization or extraction system	60

designs, especially for evacuation times and structural fire safety performance design. The addition of safety factors to performance criteria permits the designer to make a conservative assessment while allowing for a smaller margin of error by accounting for uncertainty in the models, the input data and the assumptions. The following are some examples found in the literature of the use of safety factors in fire safety engineering. These factors are also summarized in Table 14.

● In the BSI Draft Code [2], a safety factor of 2, applied to the calculated evacuation time, is proposed for assessing actual travel time of people not familiar with the premises. The BSI Code also suggests using a safety factor ranging between 1 and 1.5 applied to the design fire load to avoid the occurrence of structural collapse. A safety factor of 1.5 is used for tall unsprinkled buildings.

● Deakin and Cooke [8] reported a safety factor ranging between 2 and 3 applied to evacuation times and to times to reach untenable conditions and a safety factor between 1 and 2 applied to structural fire resistance design to avoid structural failure and fire exposure to adjacent structures.

● Johnson and Timms [14] suggested using safety factors of 2 to 3 applied to calculated escape times for determining actual evacuation times.

2.2. Probabilistic criteria

Fire protection engineering is a complex science because, in addition to determining the time-dependent physical and chemical processes, uncertainties, such as human behaviour, the conditions of doors and other openings, fire location, arrangements of

Table 14
Safety factors

Reference	Safety factor applied to	Suggested safety factor
[2]	● Calculation of occupants' travel time in evacuation	2
	● Calculation of fire load required to cause structural failure	1–1.5
[8]	● Calculation of time to reach untenable conditions	2–3
	● Calculation of primary structural member failure	2
	● Calculation of structural frame failure	1–2
[14]	● Calculation of evacuation times	2–3

combustibles, and the reliability and effectiveness of the fire suppression and detection systems, must also be determined in order to develop an overall estimate of building fire safety. The time-dependent physical and chemical processes are usually calculated using deterministic approaches. The impact of uncertainties can be estimated through probabilistic calculation and statistical analysis.

A combination of deterministic and probabilistic calculations can be used to carry out risk assessments for the overall building system. Fire risk assessment is a function of the likelihood of unwanted events and the resulting consequences or severity of these events; i.e., the risk can be evaluated as:

$$\text{Risk} = \Sigma(\text{likelihood of an event}) \times (\text{expected consequences}). \quad (3)$$

In general, a quantitative probabilistic risk assessment analysis includes the development of a number of event scenarios, an estimate of the likelihood and consequences of these scenarios, an evaluation of the risk based on Eq. (3) and finally a comparison of the calculated risks to the acceptable risks to find out whether the evaluation criteria are satisfied. Currently, probabilistic methods are not often used, however, they will increase in popularity once acceptable risk values are established and risk assessment tools become readily available. Hence, one of the major issues that must be addressed prior to carrying out a risk assessment analysis is the establishment of acceptable risk criteria.

Acceptable risk levels depend on the risk assessment objectives to be satisfied and any defined risk level is debatable. Risk levels found in the literature include the work conducted by Fitzgerald et al. [11] who cited tolerable fire damage levels for compartments and acceptable level of loss frequency in ships as the performance objectives for their client, the US Coast Guard. The design team and the user set the probabilistic performance objectives as:

- Unacceptable loss: full compartment lost to fire
- Threshold frequency of unacceptable loss: 0.033 per ship per year
- Frequency of established burning: 0.0474 per year.

Other published risk levels are shown in Table 15. These are extracted from the BSI Draft Standard Code of Practice [2], which presents some of the risk criteria (based on U.K. statistics) that society is willing to tolerate, however, general acceptance is still arguable. Table 15 indicates that, although society is willing to accept higher risk levels from incidents with a low number of casualties, fires which may result in multiple deaths, are less tolerable.

Another way to deal with probabilistic estimates is to calculate risk levels by separating estimates obtained for fire severity and likelihood (see Eq. (3)) and then set up objectives in terms of reducing the likelihood of occurrence, the severity of the incident, or both. Few studies have defined such estimates, however, Table 16, which shows a list of suggested values of incident severity and likelihood defined for the Panama Canal contingency planning [16], provides some guidance. The risk level is calculated as the product of incident severity and incident likelihood (see Eq. (3)). The calculated risk is then compared to accepted risk levels for such installations.

Table 15
Tolerability of risk [2]

Category	Probability
Maximum tolerable risk to individual member of the public	10^{-4} probability of death per year
Generally acceptable risk to individual member of the public	10^{-6} probability of death per year
Individual risk from fires only	
(1) At home or sleeping	1.5×10^{-5} per individual per year
(2) Elsewhere	1.5×10^{-6} per individual per year
Risk of multiple deaths from fires only	
(1) > 10 deaths	5×10^{-7} per building per year
(2) > 100 deaths	5×10^{-8} per building per year

Table 16
Risk ranking matrix [16]

	Value
Severity	
Minor	Potential serious health impact or less than 1 day disruption of operations
Serious	Potential for a single fatality or 1 day disruption of operations
Extensive	Potential for 2 to 10 fatalities or 2 to 10 days disruption of operations
Catastrophic	Potential for more than 10 fatalities or more than 10 days disruption of operations
Likelihood	
High	More than 0.1 probability of occurrence per year
Moderate	Between 0.1 and 0.01 probability of occurrence per year
Low	Between 0.01 and 0.001 probability of occurrence per year
Very low	Less than 0.001 probability of occurrence per year

To show the use of Table 16, an example is helpful. Assume that the acceptable risk level, as established by the design team, is 5×10^{-3} probability of death per year. If an event of serious severity is permitted to happen (i.e., max. one fatality), then the likelihood of that event should be not more than 'very low' (i.e., less than probability of 10^{-3}). This is because, in this instance, according to Eq. (3), the calculated risk is less than 10^{-3} (1×10^{-3}) which in turn is less than the acceptable risk level of 5×10^{-3}. It should be mentioned that the proposed values were established for the Panama Canal by considering the importance of that facility and the economic consequences of disrupting its operation. For other installations and buildings, the owner and designer should work together to establish similar thresholds. In building codes, thresholds are implicitly established by those who adopt the codes.

Table 17 is another list of suggested risk levels, in terms of incident severity and likelihood, proposed for use for fire and explosion hazards on offshore oil platforms as reported by Finucane [10]. The table can be used in a similar fashion to the risk assessment process presented by Long and John [16] and according to Eq. (3). Finucane [10] also proposed, as the acceptable individual risk, a value ranging between 10^{-5} and 10^{-4} and, as the unacceptable risk per individual, a value higher than 10^{-3} probability of death per year. The suggested risk levels are similar to the ones shown in Table 16. These values, how-

Table 17
Definitions of incident severity and incident likelihood [10]

	Definition
Severity	
Catastrophic	Multiple deaths
Fatal	A single death and/or multiple severe injuries
Severe	A single severe injury and/or multiple minor injuries
Minor	At most a single minor injury
Likelihood	
Frequent	Likely to occur repeatedly during the operational life of the installation
Probable	Likely to occur from time to time during the operational life of the installation
Occasional	Likely to occur once during the operational life of the installation
Remote	Unlikely to occur during the operational life of the installation
Improbable	Very unlikely to occur during the operational life of the installation
Implausible	Extremely unlikely to occur during the operational life of the installation

ever, need to be discussed further before they are accepted by society and widely used.

3. Discussion and conclusions

3.1. Discussion on deterministic criteria

The different deterministic criteria shown in this paper, also summarized in Table 18 which presents lower and upper limits for different criteria, are currently used for design and in computer models. However, there is still much discussion as to the exact values that should be used. Add to this, the criteria are, in some instances, different from one reference source to another. The differences can, however, be attributed to the fact that some are addressing general types of occupancies and some are addressing only a specific type of occupancy. Further, the range of variance of proposed values varies according to the performance criteria being established. For instance, levels of O_2 and CO (life safety) do not vary considerably from one occupancy to another because the limits for untenable conditions are similar for all occupants. Stringent values on tenability limits may correspond to occupant unfamiliarity, physical and mental condition and age. Glass breakage temperature levels, on the other hand, can vary significantly depending on the type of glass used. Furthermore, when establishing criteria, the

Table 18
Summary of lower and upper limits of deterministic criteria

Stage	Suggested deterministic criteria	Lower limit	Upper limit
Pre-flashover (ignition and fire growth)	Radiant heat flux for ignition (kW/m^2)		
	● pilot	12	27
	● spontaneous	–	28
	Surface temperature for ignition (°C)		
	● pilot	270	350
	● spontaneous	–	600
	Heat flux for ignitability (kW/m^2)	10	40
	Maximum heat release rate (kW/m^2)	250	500
Flashover	Time to reach flashover		
	● Temperature (°C)	–	600
	● Radiation (kW/m^2)	–	20
Post-flashover	Thermal insulation of a separating structure (°C)		
	● average	140	200
	● maximum	180	240
	Structural steel temperature (°C)	–	538
	Critical received radiation (kW/m^2)	10	50
	Glass breakage temperature (°C)		
	● ordinary glass	100	175
	● tempered glass	270	350
Pre-flashover (life safety)	Convection heat (°C)	65	190
	Radiation heat (kW/m^2)	2.5	2.5
	Oxygen (%)	10	15
	Carbon monoxide (ppm)	1400	1700
	Carbon dioxide (%)	5	6
	Hydrogen cyanide (ppm)	–	80
	Upper gas layer temperature (°C)	183	200
	Visibility (m)		
	● primary fire compartments	2	3
	● other rooms	10	–
	Critical time to reach untenable limits (min)		
	● unprotected zones	2	6
	● partially protected zones	5	10
	● protected zones	30	60

values depend on the use of the occupancy and the categorization of the occupancy and occupants. For example, the evacuation time allowed in a hotel should be higher than the evacuation time allowed in an office building since, in the former, the occupants would not be familiar with the building while occupants in the latter building are not only familiar with the building but may also have regular egress drills.

Deterministic analyses may require the inclusion of safety factors. From an overview of the literature, the proposed values for safety factors range, in general, from 1 to 3. A low value (i.e., 1) indicates that the level of uncertainty is low. A high value (i.e., 3) is an indication of high uncertainty in the calculation of the performance of the fire safety systems. Most authors or standards set a minimum safety factor value of 2 when applied to calculated evacuation times so that occupants have sufficient time to reach a safe place. In the cases of large floor areas, large numbers of occupants and non-familiarity with the occupancy, the calculated evacuation times may be factored by 3 or more. Furthermore, when means of suppression, such as sprinklers, are provided, the safety factors applied to structural fire resistance may be as low as 1 as the sprinklers are shown to detect and suppress the fire in more than 95% of the cases [17].

Finally, although the use of deterministic calculations provides a picture of what the conditions in a room may be at a given time, or what the performance of individual structural components is, it has limited ability in considering the entire building with its fire protection systems, functions and occupants as a system. This limitation is significant as it does not allow the quantification of the overall safety level in a building.

A comparison of alternative designs is limited only to specific elements. To obtain an overall assessment of a building, deterministic computations must be combined with probabilistic analysis.

3.2. Discussion on probabilistic criteria

In contrast to deterministic calculations, probabilistic methods may be able to consider the whole building (not element by element evaluation) and to provide risk estimates. In probabilistic evaluations, there are many factors that could affect the occurrence of a fire, its development and the egress of the occupants. The objective is to estimate risk levels using the likelihood of a fire incident occurring and its potential consequences (injury, death, etc.). The risk criteria can be established through statistical data, however, in order to gain society's acceptance, such an approach must become widely used. The risk levels, calculated using probabilistic risk assessment methods, are then compared to the risk criteria to determine whether the proposed designs are acceptable. Presently, the probabilistic approach is rarely used because of the lack of appropriate risk assessment tools and the unavailability of specified risk levels acceptable to society. However, with the introduction of performance-based codes, the availability of risk assessment models and the establishment of risk levels acceptable to society, the probabilistic approach will be the preferred method in performance-based design as it quantifies the risk levels and allows the identification of designs that will have acceptable risk levels at minimum cost.

3.3. Conclusions

This paper presented and discussed deterministic and probabilistic criteria used for the design of fire protection for buildings. These criteria are used in conjunction with deterministic or probabilistic engineering calculations for the design of those fire protection features in buildings which cannot be designed by following the prescriptions of existing codes. The paper demonstrates that, for many aspects of fire safety design, performance criteria have already been established and used; e.g., for cases where a fire safety design is conducted using alternative designs that are equivalent to the existing prescriptive codes. Although performance criteria, such as those given, are becoming universally accepted, this paper indicated that there are still variations in the criteria used. The need for performance criteria and the need for established life safety levels will become increasingly important with the introduction of performance-based codes.

Under a performance-based code design environment, it is expected that not only the use of engineering calculations in design will increase but also more innovation in building designs and products will emerge. This will increase the need for standardizing performance criteria and the need for developing society-acceptable risk levels. This need can be satisfied by the development of risk assessment models which utilize both deterministic calculations and probabilistic methods to evaluate the risk to life and property in a building based on the building characteristics and the fire protection features installed. The establishment of criteria and the development of risk assessment models that use both deterministic and probabilistic methods to assess the life risks in buildings from fires will lead to cost-effective and safe fire protection designs. Finally, one thing is certain, that the introduction of performance-based codes will require a higher level of expertise and knowledge.

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References

[1] C. Barnett, M.R. Simpson, Fire Code Review: New Zealand's Performance-based Fire Code, Proceedings of the First International ASIAFLAM Conference 1995, InterScience Communications, Hong Kong, March, 1995, pp. 27–40.

[2] BSI Standards, Draft British Standard Code of Practice for The Application of Fire Safety Engineering Principles to Fire Safety in Buildings, Panel FSM/-/5 and Technical Committee FSM/24 Fire Safety Engineering, London, UK, 1994.

[3] A.H. Buchanan, Fire Engineering Design Guide, Centre for Advanced Engineering, University of Canterbury, New Zealand, 1994.

[4] R.W. Bukowski, V. Babrauskas, Developing rational, performance-based fire safety requirements in model building codes, Fire and Materials 18 (3) (1994) 173–191.

[5] R.W. Bukowski, F.B. Clarke, J.R. Hall Jr., S.W. Stiefel, Fire Risk Assessment Method: Description of Methodology, National Fire Protection Research Foundation, Quincy, MA, 1990.

[6] CAN/ULC-S101-M89, Standard Methods of Fire Endurance Tests of Building Construction and Materials, Underwriters' Laboratories of Canada, Scarborough, Ontario, Canada.

[7] CIB W14 Workshop, Design guide structural fire safety, Fire Safety Journal 10 (2) (1986) 75–137.

[8] G. Deakin, G. Cooke, Future codes for fire safety design, Fire Safety Journal 23 (2) (1994) 193–218.

[9] P.J. DiNenno (Ed.), SFPE Handbook of Fire Protection Engineering, 2nd edn, Society of Fire Protection Engineers, Boston, MA, 1995.

[10] M. Finucane, The adoption of performance standards in offshore fire and explosion hazard management, Fire Safety Journal 23 (2) (1994) 171–184.

[11] R.W. Fitzgerald, R.C. Richards, C.L. Beyler, Fire safety analysis of the polar icebreaker replacement analysis, Journal of Fire Protection Engineering 3 (4) (1991) 137–150.

[12] H. Frantzich, R. Jonsson, T. Rantatalo, The Swedish Regulatory Approach, International Symposium and Workshops on Engineering Fire Safety in the Process of Design: Demonstrating Equivalency, Proceedings Part 3, CIB W14: Fire Safety Engineering, University of Ulster at Jordanstown, Antrim, Northern Ireland, September 13–16, 1993, pp. 71–109.

[13] G.V. Hadjisophocleous, N. Benichou, A.S. Tamim, Development of performance requirements for fire safety—literature review of performance-based fire codes and design environment, Journal of Fire Protection Engineering (submitted).

[14] P. Johnson, G. Timms, Performance-based Design of Shopping Centre Fire Safety, Proceedings of the First International ASIAFLAM Conference 1995, InterScience Communications, Hong Kong, 1995, pp. 41–50.

[15] A.K. Kim, B.C. Taber, The effect of sprinkler location and activation time on the protection of glazing systems, International Fire Protection Engineering Institute-V, Ottawa, Canada, May 21–31, 1989.

[16] M.H. Long, J.I. John, Risk-based emergency response, ER93 Conference, The Practical Approach to Hazardous Substances Accidents, St. John, NB, Canada, September 7–10, 1993.

[17] H.L. Malhotra, Fire Safety in Buildings, Department of the Environment, Building Research Establishment, Report 987 (K), England, 1986.

[18] M.A. O'Hara, Prior knowledge, The Construction Specifier 46 (9) (1993) 94–102.

[19] C. Quaglia, Deterministic design, International Fire Safety Engineering Conference: The Concepts and the Tools, Conference Papers, Forum for International Cooperation on Fire Research, CSIRO, Sydney, Australia, 1992.

[20] S. Scherfig, Development of a performance fire code and a design system for fire safety in buildings, Nordic Fire Safety Engineering Symposium, 'Development and Verification of Tools for Performance Codes', Fire Technology Laboratory, Technical Research Centre of Finland and Forum for International Cooperation on Fire Research, Espoo, Finland, August 30–September 1, 1993.