DEVELOPMENT OF PERFORMANCE-BASED CODES, PERFORMANCE CRITERIA AND FIRE SAFETY ENGINEERING METHODS

G.V. Hadjisophocleous
Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario K1S 5B6, Canada

N. Bénichou
Fire Research Management Program, National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada

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ABSTRACT

This paper presents the results of a literature survey, undertaken by the National Research Council of Canada, on the efforts to move from prescriptive building regulations to performance-based regulations. This survey has revealed that, in recent years, in many countries around the world, building codes are moving from prescriptive- to performance-based requirements. This increasing world-wide tendency to move toward performance-based codes is due, in part, to the negative aspects of the prescriptive codes, to advances made in fire science and engineering, to the need for codes to use fire safety engineering principles within the context of their regulations, and to the global harmonization of regulation systems. In addition, a performance-based code approach improves the regulatory environment by establishing clear code objectives and safety criteria and leaving the means of achieving these objectives to the designer. Hence, the codes will be more flexible in allowing innovation and more functional. Performance-based codes will also permit the use of modelling tools for measuring the performance of any number of design alternatives against the established safety levels. In this way, improved fire safety designs at reduced costs might be achieved.

This paper also describes the required steps for developing performance-based codes. The description outlines a set of objectives formulated based on a combination of international formulations. Also presented are some of the performance design criteria for quantifying the desired fire safety objectives and some of the existing fire safety design tools for quantifying the performance objectives. The full utilization of the existing tools in performance-based design will depend on the systems in place to educate fire designers and fire officials in their use and their continued validation with realistic fire test data. Finally, a brief discussion about the necessary design documentation to be submitted to authorities for approval of the fire safety design is outlined.

1. INTRODUCTION

Building codes may be classified as prescriptive or performance-based in nature. Prescriptive codes obtain their names from the fact that they prescribe specifically what to do in a given case. Performance codes express the desired objective to be accomplished and allow the designer to use any acceptable approach to achieve the required results.

1.1 Prescriptive Codes

Since the beginning of this century, prescriptive codes have been used in specifying fire protection systems in buildings. These codes have evolved over many decades, with newer requirements being imposed over existing ones. As a result, prescriptive codes have become complex and are often difficult to use for new technologies and change in practices. Prescriptive codes are used in most countries and many people argue the benefits of replacing them. Although prescriptive codes have the advantage in that they enable a straightforward evaluation of determining whether or not the established requirement has been met, they have certain drawbacks, as follows [1]:

- they specify their requirements with no statement of objectives;
- they do not promote cost-effective designs;
- they provide very little flexibility for innovative solutions and unusual situations;
- they presume that there is only one way of providing the level of safety, which in itself is not stated;
- they cannot be used for most of today’s large complex buildings.

1.2 Performance-Based Codes

In recent years, building codes, regulations and standards have been going through a transition from prescriptive-based to performance-based. Many countries are in the process of developing performance-based fire safety regulations and the engineering criteria required to support these regulations. The reason behind the move towards the performance approach is the expected advantages that the performance-based fire safety design can offer over the prescriptive design. These advantages can be summarized as follows [1]:

- establishing clear fire safety goals and leaving the means of achieving those goals to the designer;
- permitting innovative design solutions that meet the established performance requirements;
- eliminating technical barriers to trade for a smooth flow of industrial products;
- allowing international harmonization of regulation systems;
- permitting the use of new knowledge as it becomes available;
- allowing cost-effectiveness and flexibility in design;
- enabling the prompt introduction of new technologies to the marketplace;
- eliminating the complexity of the existing prescriptive regulations.

For performance-based codes, the biggest challenge is to define the criteria to meet the code compliance and the necessary tools to quantify these criteria. This aspect is being investigated internationally and significant progress has been made in the development of numerical methods to evaluate compliance. Later in this paper, two such fire safety design tools being developed at the National Research Council of Canada (NRC), will be presented.

This paper presents the international efforts for the development of performance-based codes in different countries and organizations around the world. The paper also describes the required steps for developing performance-based codes, including the objectives, performance design criteria that can be used in designing fire protection systems in buildings, and the design tools used to determine whether the design criteria are met by the proposed designs. Finally, a brief discussion about the necessary design documentation to be submitted to authorities for approval of the fire safety design is outlined.

2. INTERNATIONAL DEVELOPMENTS

Even though the implementation of performance-based codes is not easy to achieve, some countries have already modified their regulations to embrace the concept of performance-based codes and some are planning this modification. The major international developments in the concept of performance-based codes were detailed in Hadjisophocleous et al. [1]. The following is an updated review of the status of performance-based code developments of the countries moving towards performance-based regulations.

2.1 Japan

The Japanese activities of the Ministry of Construction (MOC), in conjunction with Building Research Institute (BRI), toward performance-based fire regulations were initiated in the early 1980s [2]. This tendency was to facilitate international trade and to permit the harmonization of international building codes. The development of a total fire safety assessment framework, using a fully performance-based design, will be used to establish equivalency with the Building Standard Law (BSL), by explicitly defining the fundamental requirements, expressing technical standards in performance terms and providing calculation methods and computer methods for predicting fire-related behaviours. After a number of years of debate, a performance-based code was introduced through the amendment by BSL. The amendment was promulgated in June 1998. Ogawa reported that since the amendment indicated that part of the performance-based code must be enforced by June 2000, work is underway to establish specific criteria and verification methods for each performance requirement. In addition, a new approval system, for solutions to meet the performance-requirements, was introduced in the amendment. In the new approval system, only the MOC or designated certified approval bodies can approve building designs. Ogawa stated that the performance-based regulatory system in Japan is still under construction, and that international activities for sharing each country's experience will contribute to the creation of a stable regulatory system under a performance environment.

2.2 Canada

The strategic planning task group of the Canadian Commission on Building and Fire Codes (CCBFC) [3] revealed in a Draft Strategic Plan its intent to focus on the development of an objective-based code. The goal was to develop a fully objective-based code in the next edition of the National Building Code of Canada (NBCC) [4]. The main reasons for this initiative were to simplify the code structure, to explicitly state its objectives, to permit innovative designs, to enable users to comply with the requirements or to offer alternative solutions that meet the performance expectations, and to reduce trade barriers in design and construction. According to the report, some of the shortcomings of the prescriptive codes were their complexity and their lack of clarity, which resulted in a broad range of interpretation. Even though the existing codes had provisions for alternative solutions, they did not specify the intent of the requirements. The report also stated some concerns with the performance approach, such as the requirements for higher technical knowledge on the part of regulators and code enforcers, for the verification of performance criteria when no published solution was available, and for the increased number of references required. In addition, the CCBFC Task Group on the Code Review and Development Process in their final report [5] stated that the new code will be completed by the year 2003. The new code will be in a single document, consisting of two sections. Section A will contain objectives and functional requirements; Section B will contain qualitative performance criteria and acceptable solutions. Section B of the 2003 code will essentially be the 1995 NBCC [4] prescriptive code with normal technical upgrades.

2.3 UK

Until 1985, the building regulations in the UK were prescriptive and were written in a language mainly understood by lawyers. The regulations have been growing in size whereas the flexibility in design was reducing. In the early 1980s, the government decided to increase flexibility in design, remove constraints and produce a more intelligent system. This led to the publication of the 1985 new regulations [6]. This set of regulations was published in 23 pages covering the functional requirements. To meet the requirements, a set of documents approved by UK Secretary of State was published. In addition, in 1994, the British Standards Institute (BSI) issued a Draft British Standard Code of Practice [7] for the application of fire safety engineering principles to the design of fire safety in buildings. BSI makes available design guides as deemed-to-satisfy solutions issued as “Approved Documents”.

2.4 Scandinavia

The Nordic building industry and fire protection community has also been advocating the performance approach, particularly in Sweden. Larsen [8] reported on the development of the fire safety code in Scandinavia. The author suggested that a way of improving the traditional prescriptive codes was to clearly define and communicate to the industry the objectives behind the code requirements. Larsen reported that the Scandinavian countries had formed the Nordic Committee on Building Regulation whose main objective was to develop a new performance-based building code. The code would unify the use of technical tools and permit flexibility in design while providing adequate life safety. Thus, levels of safety and criteria of acceptance must be clearly defined and the technical tools must be validated. A draft of a Nordic performance-based fire code has been reviewed and an official copy of the Nordic performance-based fire code is currently available in Swedish. The structure of the code consists of five levels: overall goals, functional areas, operative requirements, verification, and examples of acceptable solutions. Norway also officially introduced a set of performance regulations in 1997 [9], based on the work done by the Nordic Committee for Building Regulation. The new regulations apply mainly to large and complex buildings. However, the Norwegian building industry and local building authorities are still resistive to the new legislation because of the control system and tough measures put in-place to approve building designs. The Norwegian authority will monitor the developments for the next five years.

2.5 Australia

In Australia, a draft Building Fire Safety Systems Code is being developed. This long-term project is an effort to convert the current building code to verifiable performance requirements and to clarify and simplify code language [10]. The Australian Building Codes Board (ABCB), responsible for the development of the Australian Building Code (BCA), has published a prescriptive code in 1990, which forms the technical basis of the States and Territories building regulations. The ABCB launched the development of the first performance-based building regulation in Australia in 1996. The new performance-based BCA represents a significant development and includes performance requirements above the existing deemed-to-satisfy prescriptive provisions. The new BCA is based on a four level hierarchy, namely societal goals, functional objectives, performance requirements, deemed-to-satisfy provisions and verification methods. The verification methods are used to provide alternative solutions that can comply with the performance requirements. A number of limitations with the new performance-based code were also mentioned such as defining code objectives and performance levels. Nevertheless, the author stated that the new code has been laid for a performance-based approach in Australia. In addition, as part of the current efforts, a risk assessment model is being developed to evaluate the cost-effectiveness of fire safety measures for specific building occupancies in terms of risk-to-life and expected fire cost.

2.6 New Zealand

The new performance-based code and design methodology in New Zealand was described by Buchanan [11-13]. Buchanan gave a summary of code developments in New Zealand, which led to the establishment of the Building Industry Authority in 1991, and the publication of a fully-functional performance-based code [11], and a summary of the design methodology needed for evaluating building designs. The code is provided with approved documents to allow means for verification as well as deemed-to-satisfy solutions. The author suggested that performance codes would allow the use of new knowledge, state clearly the code objectives, specify performance requirements, and permit any solution that meets the performance requirements. Buchanan pointed out that the performance goals should specify a level of safety that was independent of the prescriptive code requirements. The fire safety requirements were divided into four categories: Outbreak of fire, means of escape, spread of fire, and structural stability during fire. For each category, five levels were defined: Objectives, functional requirements, required performance, verification methods and acceptable solutions. Because the New Zealand Building Code [11] provided the structure for measuring performance with no means for quantifying the required levels of safety, Buchanan [14] developed the “Fire Engineering Design Guide” for quantification purposes. The guide allowed the application of fire engineering to the code evaluation and review process. Finally, according to the author, education would be an important factor for the implementation of the performance-based code and for the application of the design method.

2.7 U.S.A.

In the USA, the trend of moving from prescriptive code requirements to performance-based codes started in the early 1970s [15]. The approach received some exposure and was applied to some federal buildings. In the early 1990s, strategies for changing to performance-based codes were investigated by the model code writing bodies and the National Fire Protection Association. However, there was one problem and that is, unlike other nations, the US codes are developed by three private organizations: the Building Officials and Code Administrators, the International Conference of Building Officials, and the Southern Building Code Congress International. To eliminate the complexity of using three different codes, the three organizations formed the International Code Council [16] with the intent to publish the International Building Code (IBC), initially a prescriptive building code. The IBC is supposed to be published in the year 2000. A performance guide as a companion document to the code will be published in 2000 and will provide a set of objectives, functional statements, and performance requirements. Unlike the late process of implementing performance-based regulations, the development of performance-based design methods has been on going for some time. These methods include the fire risk assessment method by the National Fire Protection Research Foundation [17], the publication of the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering [18] and computer models by Fitzgerald [19]. In addition, the SFPE has documented the performance-based fire safety and published a guide that takes the user through the different steps to perform a performance-based analysis and design in buildings [20,21].

2.8 International Standard Organization (ISO)

In 1984, the International Organization for Standardization [22] issued the International Standard ISO 6241 which provided the general principles for the preparation of performance standards in buildings, which included objectives, types of applications, contents and methods of assessment. The standard was intended to be used as a tool by international standards committees in drafting performance standards for buildings and their sub-systems. The standard gave sample definitions of the objective of a performance standard and the performance factors to be considered, such as user requirements, uses of the building and spaces, sub-systems of the building fabric and agents relevant to the building performance. It also stated that user requirements for fire safety regulations should address the outbreak of fire, spread of fire, physiological effects of smoke and heat on the occupants, alarm time, evacuation time and time that untenable conditions are reached in the building. In addition, in 1990, the ISO Technical Committee TC2, responsible for fire-related issues, formed a new sub-committee SC4 to address the evaluation and standardization of fire engineering methods. TC4 formed five working groups dealing with: application of fire safety performance concepts to design objectives; initiation and development of fires and movement of their effluent; fire spread beyond the compartment of origin; detection, activation and suppression; and evacuation and rescue. The ISO design approach resembles the approach outlined in the BSI [7].

2.9 Conseil International du Bâtiment (CIB)

In an effort to harmonize the building code development process, the Conseil International du Bâtiment (CIB) [23] issued a report describing the performance approach in building design, guidelines on how to determine performance requirements and criteria, sample performance requirements, sample solutions in relation to the requirements and sample methods for application. The report stated that prescriptive requirements were easy to work with but were less efficient and more costly than performance solutions. Similar to the ISO, CIB has formed a Working commission W14 and a Task Group TG11 to look at the issues on fire for buildings and construction, specifically performance-based building codes. W14 has formed two sub-groups to study performance-based fire safety design for buildings, namely engineering evaluation of building fire safety and validation of fire models.

3. OVERVIEW OF PERFORMANCE-BASED FIRE SAFETY DESIGN

Due to the randomness of fire and variations in building and occupant characteristics, it is difficult to set up a general step-by-step performance-based fire safety design that could apply to all buildings. Therefore, every building should be evaluated according to its specific geometric features, its use and its occupancy. However when performing a performance-based fire safety design, there are four generic steps that should be followed.

1. Identification of performance objectives and requirements.
2. Establishment of performance criteria.
3. Quantification process.
4. Presentation of design documentation to the Authority Having Jurisdiction for approval.

The general fire safety design approach is shown in Fig. 1. As illustrated in this figure, the fire safety design team has the option to follow the existing prescriptive code if it is practical and cost-effective. If the building is complex and an engineered fire safety design is thought to be beneficial, then a performance-based fire safety should be carried out along with a demonstration of equivalency with the prescriptive code.

4. FIRE SAFETY OBJECTIVES AND REQUIREMENTS

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 first step in developing performance-based building codes is to establish top levels design objectives. The goal of this task is to clearly define these objectives, in order for the designers and code officials to understand the rationale behind the code provisions and to facilitate the evaluation procedures for building designs. In some cases, the community, the insurance companies or the owner of the building may specify additional objectives. This section identifies general fire safety design objectives and requirements for the design of active and passive fire safety systems in new and existing buildings. Based on the general design objectives, a design team can establish specific fire safety objectives for the building and select an appropriate cost-effective fire safety design, which satisfies the objectives. The objectives presented in this section are based on the objectives found in the literature [1].

4.1 Overall Objectives

The overall objectives of the fire safety systems in buildings are as follows:

- To minimize risk to life and injury to people from fires. This includes, but is not limited to, incapacitation due to exposure to heat, products of combustion and structural instability due to fire.
- To minimize property loss in the building of fire origin and adjacent buildings. This includes, but is not limited to, damage or loss to building contents, spread of fire to other compartments and other buildings and structural failure of building elements and assemblies.
- To limit the economic, operational, social and environmental impacts of fires.

4.2 Fire Safety Objectives and Requirements

The following sections describe objectives and requirements, for consideration by the design team, in the following areas:

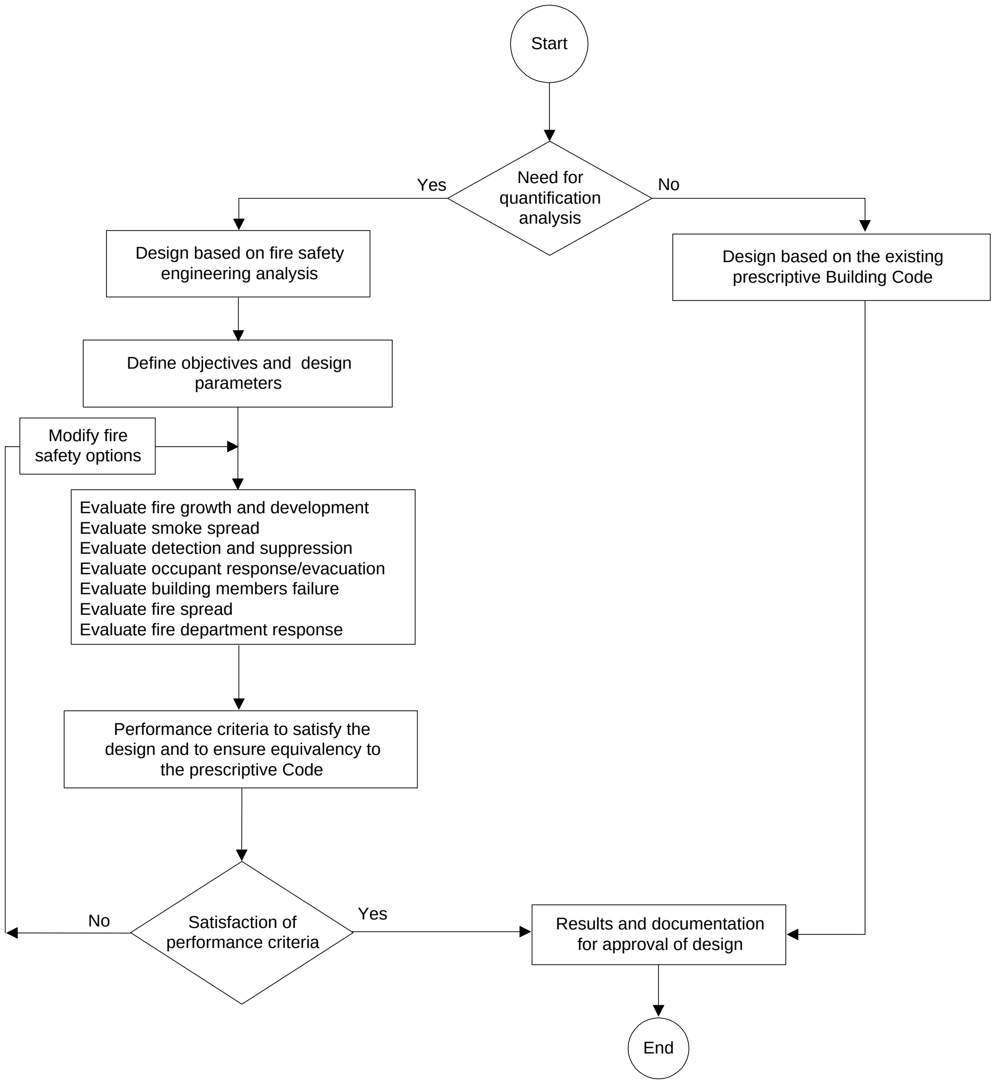

Fig. 1: General view of fire safety analysis

- fire outbreak and development;
- spread of fire and smoke;
- means of notification and evacuation;
- fire resistance and structural stability;
- emergency response operations;
- economic and social impacts;
- environmental protection.

4.2.1 Fire outbreak and development

Objective:

- To reduce the probability of ignition of fire and limit fire growth.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that the outbreak and growth of fire is minimized.

Performance Requirements:

- Construction materials shall be selected to minimize the potential of fire ignition and to limit fire growth.
- Fixed appliances, using controlled combustion of fuel, shall be installed, operated and maintained so that the potential of explosion of the appliance and fire ignition or rise of temperature of combustible building elements, is minimized.
- Measures shall be provided to reduce the probability of ignition and the growth of fire as a result of building contents and operations.

4.2.2 Spread of fire and smoke

Objective:

- To minimize the spread of fire and products of combustion from the compartment of fire origin to adjacent compartments and to other buildings.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that:
- The spread of fire and products of combustion in the building is minimized.
- The spread of fire to adjacent buildings is minimized.

Performance Requirements:

- Buildings may be divided into fire compartments, designed and maintained to minimize the spread of fire and products of combustion to other compartments of the building and to adjacent buildings.
- Buildings may be provided with automatic fire suppression systems in accordance with the life safety and property loss goals.
- Buildings may be provided with automatic smoke control systems in accordance with the life safety and property loss goals.
- Surface finishes on building elements shall be of materials that reduce fire spread, and minimize generation of toxic gases and heat.
- Buildings may be provided with fire fighting equipment for use by trained occupants.
- Buildings shall be provided with sufficient separation to minimize building to building fire spread.

4.2.3 Means of notification and evacuation

Objective:

- To notify building occupants of the need to take action in the event of a fire and to protect them from the effects of fire during evacuation.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that occupants shall be able to evacuate safely or remain in a safe place without being exposed to the harmful effects of fire.

Performance Requirements:

- Where appropriate, buildings shall be equipped with detection and occupant warning systems for notification of fire.
- Buildings shall be designed, constructed and operated with adequate, easy-to-access and easy-to-use means of egress, such as exits, doors, escape routes and safe refuge areas.
- Buildings shall be provided with appropriate fire safety plans.

4.2.4 Fire resistance and structural stability

Objective:

- To minimize building structural failure so that building occupants and emergency responders are protected and property losses and damage to the building and to adjacent properties are minimized.

Functional Requirements:

- Building structural elements shall be designed, constructed and maintained so that the load-bearing capacity is provided in accordance with the life safety and property loss goals.

Performance Requirements:

- Building structural elements shall have a fire resistance rating based on the type of structural element, the fire load, the height of the building, the fire exposure, the fire suppression measures, the occupancy and occupant profile, and the emergency team response characteristics.

4.2.5 Emergency response operations

Objective:

- To support and facilitate the operations of emergency responders.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that emergency responders can locate the fire and fire fighting and rescue operations are facilitated.

Performance Requirements:

- Where necessary, buildings shall be provided with means to identify the fire location in the building.
- Buildings shall be provided with safe external and internal access routes to facilitate rescue and fire fighting operations.
- Buildings with internal refuge areas shall be provided with means of communication with the emergency responders.
- Where appropriate, fire fighting water supplies and equipment shall be provided.

4.2.6 Economic and social impacts

Objective:

- To minimize business loss and interruption to levels acceptable to the owner, federal government authorities and the community.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that economic and social impacts resulting from a fire are minimized.

Performance Requirements:

- Fire safety measures shall be implemented to limit damage to ongoing business viability, to valuable building contents, and to buildings of historic value.

4.2.7 Environmental protection

Objective:

- To minimize environmental damage from the effects of fire.

Functional Requirements:

- Buildings shall be designed, constructed and operated so that, in the event of a fire, the release of hazardous materials to the environment is minimized.

Performance Requirements:

- Buildings shall be provided with measures to minimize the release of hazardous substances to air, water, and land in the event of a fire.

5. PERFORMANCE CRITERIA

The adoption and success of performance-based codes depend 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. Most prescriptive codes allow for alternative designs, as long as the safety levels they provide are equivalent to that intended by the code. Because of this equivalency clause, a number of buildings are currently designed 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. In the following section, a discussion on the deterministic and probabilistic criteria is presented and the details of these criteria can be found in Hadjisophocleous and Bénichou [24].

The different deterministic criteria summarized in Table 1, which presents lower and upper limits of various criteria, are currently used for design and in computer models. However, there are still many arguments as to the exact values that should be used. In addition, the criteria are, in some instances, different from one 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 levels of untenable conditions are within the same range for most of the occupants. Stringent values of untenable conditions 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 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 they may also have regular egress drills.

Deterministic analyses may require the inclusion of safety factors. The proposed values of safety factors, in the literature [24], 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 the 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 can be as low as 1 as the sprinklers are shown to detect and suppress the fire in more than 95%.

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.

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

Table 1: 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 (kWm^{-2}) • Pilot • Spontaneous	 12 -	 27 28
	Surface temperature for ignition (°C) • Pilot • Spontaneous	 270 -	 350 600
	Heat flux for ignitability (kWm^{-2})	10	40
	Maximum heat release rate (kWm^{-2})	250	500
Flashover	Time to reach flashover • Temperature (°C) • Radiation (kWm^{-2})	 - -	 600 20
Post-flashover	Thermal insulation of a separating structure (°C) • average • maximum	 140 180	 200 240
	Structural steel temperature (°C)	-	538
	Critical received radiation (kWm^{-2})	10	50
	Glass breakage temperature (°C) • ordinary glass • tempered glass	 100 270	 175 350
Pre-flashover (life safety)	Convection heat (°C)	65	190
	Radiation heat (kWm^{-2})	2.5	2.5
	Oxygen (%)	10	15
	Carbon monoxide (ppm)	1,400	1,700
	Dioxide monoxide (%)	5	6
	Hydrogen cyanide (ppm)	-	80
	Upper gas layer temperature (°C)	183	200
	Visibility (m) • primary fire compartments • other rooms	 2 10	 3 -
	Critical time to reach untenable limits (min.) • unprotected zones • partially protected zones • protected zones	 2 5 30	 6 10 60

order to gain society's acceptance, it is imperative for such an approach to 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.

6. QUANTIFICATION PROCESS

Once the identification of objectives and establishment of performance criteria have been completed, the quantification process of the different components of the fire safety design may be carried out. For convenience and ease, the literature (BSI [7] and Australian Design Guidelines [25]) has shown that it is better to conduct the evaluation process for a number of separate sub-systems. The reason for this is that if there is a need to design one particular feature of a building (e.g. detection), the fire safety engineer does not have to go through the whole process of design. For quantification process, the following number of design parts should be considered:

1. Fire Outbreak and Development;
2. Spread of Smoke;
3. Spread of Fire;
4. Fire Resistance and Structural Stability;
5. Fire Detection;
6. Fire Suppression;
7. Emergency/Fire Fighting Response Operations;
8. Means of Notification and Evacuation;
9. Continuity of Operations;
10. Environmental Protection.

Then the quantification process can be used in three different ways:

1. One part (1 to 10) is used in isolation for one specific fire scenario. This may occur when the fire safety designer is analysing a particular aspect of the design.
2. Hazard analysis of selected scenarios.
3. Fire risk analysis where all the parts are used along with all possible scenarios. The probabilities of the scenarios are added up proportionally to determine the most safe and cost-effective design.

6.1 Fire Safety Engineering Design Tools

Fire safety in buildings is an interaction among all the components of the fire safety system which includes fire outbreak, fire growth, fire and smoke spread, the response of building elements to fire, the occupant response to fire and the fire service response to fire. In order to develop a building fire safety design, it is necessary to determine the behaviour of a fire in a fire compartment from ignition to decay. Therefore, it is essential that the designers have at their disposal the means to predict the level of life safety for any particular design. The means are, in general, in the form of fire engineering computer models that can be used to estimate the performance of building fire safety systems and evaluate the compliance with the performance criteria set initially by the design team.

Over the past few years, considerable effort has been put into the development of fire engineering computer models. Fire models can be grouped into two categories: probabilistic or stochastic fire models and deterministic fire models. Probabilistic fire models involve the evaluation of the probability of risk due to fire based on the probabilities of all parameters influencing the fire such as human behaviour, formation of openings and distribution of fuel load in the compartment of fire origin. Deterministic fire models are based on physical, chemical and thermodynamic relationships and empirical correlations used to calculate the impact of fire. Deterministic models can be very simple requiring a short computing time or highly complex requiring hours of computation. Typically, deterministic models can be classified as zone models and field models.

There is no fire model that is comprehensive for all fire applications. The selection of a fire model to be used for an application depends on a number of factors including understanding the limitations and assumptions used in the model, validation of the model, documentation accompanying the model and ease of use [1]. Further, when using a fire model, it is wise to determine the sensitivity of the output to changes in the input to determine if changes in the data or the model assumptions and applicability will lead to a different decision. The sensitivity analysis will determine the most dominant and significant variables. Furthermore, fire safety engineering models can provide a good estimate of the effects of fire, however, the randomness of fire is such that the results may not be precise. When a user has some doubts about a model, the user should establish from the literature the appropriateness of the results of the model.

6.1.1 NRC fire engineering models

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.

Around the world, efforts are underway to develop fire safety models with NRC taking a leading role. NRC has been developing fire risk-cost assessment models for different occupancies. These models assess the overall fire risk inside buildings. In the following sections, two NRC models, FiRECAM™ (**Fi**re **R**isk **E**valuation and **C**ost **A**ssessment **M**odel) [26,27] and FIERAsystem (**FI**re **E**valuation and **R**isk **A**ssessment **system**) [28] will be described.

Description of FiRECAM™

FiRECAM™ assesses the performance of a fire safety design in terms of two decision-making parameters: the expected risk to life (ERL) and the fire cost expectation (FCE). The ERL is the expected number of deaths per year as a result of all probable fires that may occur in a building. The FCE is the expected total fire cost which includes the capital cost for passive and active fire protection systems, the maintenance and inspection costs for the active fire protection systems and the expected losses resulting from all probable fires in the building. The ERL is a quantitative measure of the risk to life from all probable fires in a building, whereas the FCE quantifies the fire cost associated with a particular fire safety design. The separation of life risks and protection costs in FiRECAM™ eliminates the difficulty of assigning a monetary value to human life and allows for a separate comparison of risks and costs. The ERL value can be used to determine whether a fire safety design meets the performance code requirements, or whether it provides a level of safety that is equivalent to that of a code-compliant design in a prescriptive code; whereas the FCE value can be used to identify cost-effective designs.

To calculate the ERL and FCE values, FiRECAM™ considers the dynamic interaction among fire growth, fire spread, smoke movement, occupant evacuation and fire department response time. These calculations are performed by a number of sub-models interacting with each other, as shown in Fig. 2. The computer model includes two optional sub-models (Building and Risk Evaluation and Fire Department Response) that can be run if the building fire characteristics and fire department response are not considered typical. The Boundary Element Failure and Economic sub-models are run only once to obtain the failure probability values of boundary elements and the capital and maintenance costs of fire protection systems. The other ten sub-models are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from all probable fire scenarios.

FiRECAM™ uses statistical data to predict the probability of occurrence of fire scenarios, such as the type of fire that may occur or the reliability of fire detectors. Mathematical models are used to predict the time-dependent development of fire scenarios, such as the development and spread of a fire and the evacuation of the occupants in a building. The life hazard to occupants posed by a fire scenario is calculated based on how fast the fire develops and how quickly the occupants evacuate the building in that scenario. The life hazard calculated for a scenario multiplied by the probability of that scenario gives the risk to life from that scenario. The overall expected risk to life to the occupants is the cumulative sum of all risks from all probable fire scenarios in a building. Similarly, the overall expected fire cost is the sum of fire protection costs and the cumulative sum of all fire losses from all probable fire scenarios in a building. The expected risk to life is expressed as:

$$\text{Expected Risk to Life} = \sum_{\text{all i}} \left(P_i \times C_i\right) \qquad (1)$$

where **Σ** represents the summation of all probable fire scenarios, P_i is the probability of a fire scenario C_i is the expected number of deaths from that fire scenario.

A fire scenario is a description of the conditions of the controlling parameters that would govern the outcome of the fire development and the evacuation of the occupants. For example: (1) location of the fire in a building; (2) type of fire occurring (smouldering fire, small flaming fire, or flashover fire); (3) fire compartment door being

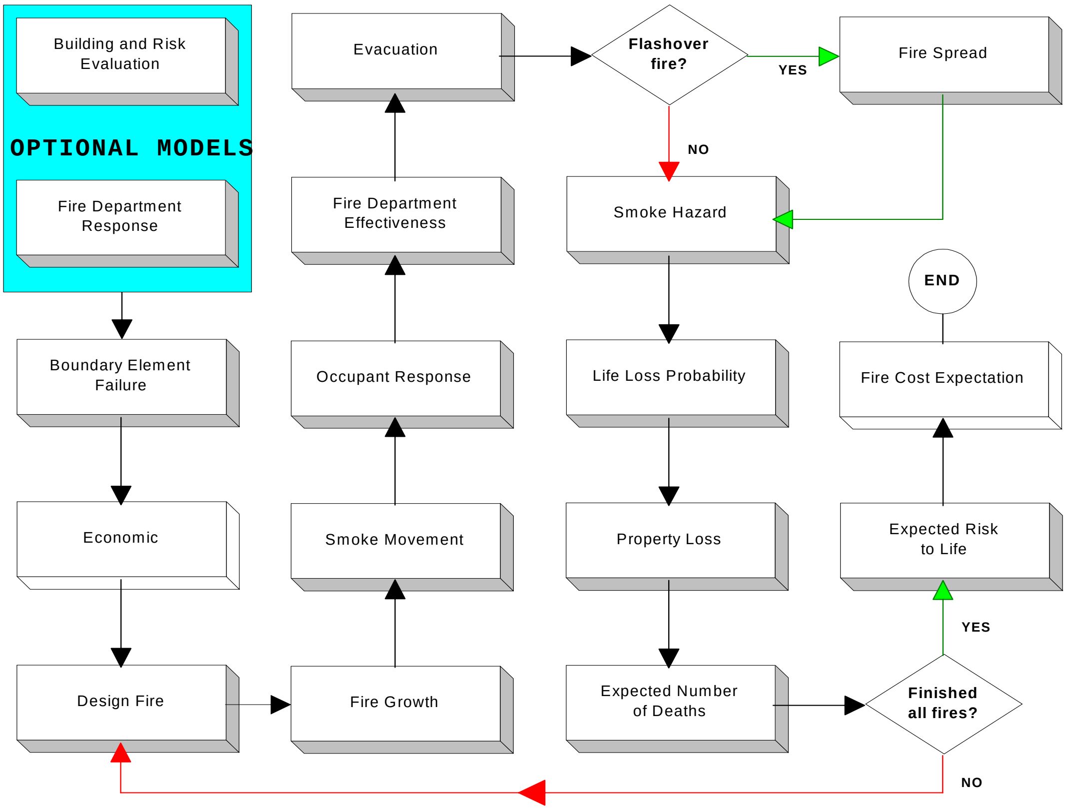

Fig. 2: FiRECAM™ flowchart

open or closed; (4) installed smoke detectors operational or not; (5) installed sprinklers operational or not. The probability of a controlling parameter in a particular condition can be obtained from statistics (e.g., probability of flashover fires occurring) or, in the absence of such statistical information, from expert opinion (e.g., probability of the door to the compartment of fire origin being open). For each fire scenario, FiRECAM™ uses time-dependent deterministic sub-models to calculate the life hazard to the occupants and fire losses. Details on the sub-models of FiRECAM™ can be found in Yung et al. [27].

Description of FIERAsystem

To extend the risk assessment concepts developed in FiRECAM™, a new computer model is now being developed to evaluate fire protection systems in light industrial buildings, with a primary focus on warehouses and aircraft hangars. The concept of risk assessment in the new model follows similar steps as those shown in Fig. 2 for FiRECAM™. However, in the early stages of development, it was recognized that there are substantial differences between light industrial buildings and the apartment and office buildings modelled previously. These differences include fire scenarios, smoke movement, and fire spread.

To follow the approach of performance-based codes, FIERAsystem is based on a framework that allows designers to establish objectives, select fire scenarios and evaluate the impact of each of the selected scenarios on life safety, property protection and business interruption.

The framework leads the user through a series of steps in setting up the problem. These steps include definition of building characteristics and occupant characteristics, identification of fire safety objectives and appropriate performance criteria, selection of potential fire scenarios, fire protection options and calculation procedures.

Building characteristics include details of all building compartments, their boundaries, type of construction and ventilation openings, as well as, properties of the contents and types of fuels present. In addition, the user may define the proximity of nearby properties and the ignition characteristics of their exterior surfaces. The model uses this information to determine whether fire may spread to neighbouring properties.

Occupant characteristics required by FIERAsystem include the number of occupants, their ages, locations and physical disabilities, the presence of groups, whether occupants are trained in fire extinguishment and whether they are required to try to suppress the fire. These characteristics were identified as the ones affecting the ability of the occupants to receive and interpret fire cues and warning signals, and their ability to evacuate [28].

Fire safety objectives for the building and design criteria are defined by the user. Objectives deal with fire ignition and development, fire and smoke spread, life safety, fire fighting operations, structural stability, property protection, continuity of operations and environmental protection. These objectives may deal with one aspect of the fire problem (e.g., prevent the occurrence of flashover for a given time) or they may deal with the whole building system (e.g., no occupants subjected to critical conditions).

The framework allows the user to choose from a variety of fire scenarios expected in these types of buildings. The fire scenarios included in this version of the model are:

- solid fuel fires in a small compartment (e.g., an office);
- liquid pool fires in an open or enclosed space;
- storage rack fires;
- t^2 fires (i.e., the heat release rate is assumed to be proportional to the square of the elapsed time, which is often used to simulate fires).

The selected scenarios are then considered by the model, one by one, and their impact on the established objectives, such as life safety and property protection, are evaluated.

The framework allows the user to choose the fire protection options for the building. These include passive systems, such as fire resistance ratings of the building elements, exit routes and refuge areas, as well as automatic fire protection systems such as automatic suppression systems, fire detection systems, smoke control and alarm systems. Manual fire protection systems, such as fire hydrants, hoses, extinguishers and pull-bars, as well as occupant training, can also be considered. The impact of these systems on fire development, fire and smoke spread and occupant response and evacuation are evaluated by the model. The reliability and effectiveness of these systems are critical in evaluating their impact for each scenario. Reliability and effectiveness values are presently obtained from statistics, however submodels are under development to enable better estimates of these values.

For each fire scenario, FIERAsystem calculates life hazard and property losses. Life hazard is defined as the number of deaths from the effects of fire and smoke. Property losses include damages to the building and its contents, as well as, losses due to business interruption. The procedure followed for this calculation is as follows:

The fire scenario in a compartment is identified, as well as the types of fires that may occur in adjacent compartments due to fire spread from the compartment of fire origin. The time of fire spread to the adjacent compartments depends on the time of failure of the boundaries separating the compartments computed by the boundary failure models, as well as on the thermal radiation fluxes from the hot gases in the compartment. The development of these subsequent scenarios is then computed by the appropriate fire development model resulting in heat release rates with time in each of the compartments for each fire type, as well as thermal radiation heat fluxes due to these fires.

Following the fire development calculation, the smoke movement model computes smoke movement from the compartment of fire origin throughout the building. The heat release rate (HRR) computed by the fire development model for the fire in the compartment of fire origin is used as input to the smoke model.

Using the concentrations and temperature of the hot gases in each compartment calculated by the smoke movement model, a smoke hazard probability is computed based on the dosage received by the occupants in that compartment as expressed by the fractional incapacitating dosage (FID) values and the temperature of the hot gases.

In addition to the smoke hazard, a thermal radiation hazard is computed based on the radiation fluxes at a height of 1 m due to the fire plume and the hot gases.

Combining the probability of death from smoke and thermal radiation, an overall time dependent probability of death is computed for each compartment. This probability is then used to calculate the number of people that may die from that scenario by multiplying it by the residual live population in that compartment. The residual population is computed by the occupant response and evacuation model.

Property losses are computed using the costs of the building, its fire protection systems and its contents, which are provided by the user. The sensitivity of the different parts of the building and its contents to heat, smoke and water are also input. Damages to the building and its contents are then estimated for the fire scenarios selected by the user based on information from the fire development and smoke movement submodels and the sensitivity of the building and contents. These damage estimates can then be used along with the cost information to estimate the value of the property loss to the building and its contents.

Similar to the FiRECAM™ system, once the consequences of each of the scenarios are determined, the probabilities of these scenarios are used to calculate the ERL and FCE parameters. The probabilities of the scenarios are user input to allow the user flexibility in identifying the frequency of the scenarios selected.

7. PREPARATION OF DESIGN DOCUMENTATION

Once a building has been designed, it is necessary to document the design so that the appropriate authority can review it, as well as used if for future references in case of building renovation or change of occupancy. The design documentation is an essential element of the fire safety design process. The documentation must be done thoroughly to facilitate the review process.

The design report must include at least the following information:

- Design team: This describes the participants in the design process. A brief description of their position, their qualifications, and their responsibilities in the design.
- The objectives and scope of the design: This is a description of why the design was undertaken. This section also presents the extend of the analysis and what is to be included in this analysis.
- Information on the building: This is a description of the layout of the building, its uses, its contents, construction materials, the fire protection systems and the characteristics of the occupants.
- The agreed upon fire safety objectives: These are the fire safety objectives defined by the design team. There should be some rationale on why these objectives were selected.
- Performance criteria: Each fire safety objective should be judged against a performance criterion to judge the adequacy of the design. The performance criteria can be based on the existing prescription or accepted values.
- Fire scenarios used: This is a description of the fire scenarios used in the analysis along with their assumptions and restrictions. There should also be some indication of the basis of choosing these scenarios.
- Design calculations: This is a description of the type of calculations (deterministic or probabilistic) that were performed. There should be an indication of why the type of calculation was used.
- Assumptions used in the analysis: This is a description of all the assumptions and the engineering judgement applied to the design along with the rationale of why these were implemented.
- Engineering tools used in the analysis: This is a description of computer tool used to do the analysis. The limitations and assumptions used in the tool should be clearly indicated. There should also be an indication why the tool was used.
- Evaluation of the analysis results: A section on the evaluation of the results against the performance criteria must be shown in the document to indicate that the design is satisfactory for the assumptions used.
- Drawings: All drawings (maps, analysis figures, etc.) should be included in the documentation.
- References: Technical data, fire test results, literature reports, tool documentation and any other information used should be referenced in the documentation report.

Based on the design documentation provided, the enforcing authority can make a decision whether or not compliance with the established requirements has been met. During the life of the building, regular inspections must be done to ensure that the use of the building has not changed from the original and that none of the original design assumptions have changed from those on which the building design was originally accepted.

8. SUMMARY AND CONCLUSIONS

This paper presented an update on the efforts made to move towards performance-based codes and discussed the elements of a performance-based code, as well as, the need to establish performance criteria that can be used to evaluate fire safety designs.

It can be stated that prescriptive codes have the advantage that designers can do a design by just following prescriptions and that code officials can easily determine whether a design follows code requirements. Prescriptive regulations, however, restrict innovation, limit the application of novel construction technologies, and do not have clear statements of the safety objectives to be achieved. Performance-based codes, on the other hand, improve the regulatory environment by establishing clear code objectives and safety criteria and leaving the means of achieving these objectives to the designer. The major international shifts to performance-based regulations have been happening mainly in New Zealand, Australia, Scandinavia, UK, Japan, Canada, and USA with the first three spearheading the group. In addition, the move towards performance-based codes recognizes that a large number of buildings will actually be designed following prescriptive-based codes. Only complex large buildings will benefit from the introduction of performance-based codes.

The development of performance-based codes requires defining clear objectives. The overall objectives are life safety and property protection. However, these can be formulated into many sub-categories. Based on the existing objectives, internationally, a set of objectives was established and the users can pick the objectives that best suit their needs. Along with the objectives, design criteria, for quantifying the desired fire safety objectives must be defined. These criteria are probabilistic and deterministic. Range values were provided and the fire safety engineers can make a judgement on what to use. The need for both design criteria and 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 both standardizing performance criteria and 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. Two models, being developed at NRC, that assess fire risk and expected costs in buildings were presented. These models allow the user to identify cost-effective design solutions that would achieve acceptable levels of safety for the occupants in buildings. However, the use of computer-based tools to evaluate compliance with code requirements will succeed if they continue to be validated using full-scale test data and if training programs are designed to educate users on the application of these tools.

Finally, the success of adopting performance codes will depend on the availability of calculation systems to support the user in trying to meet code objectives and the availability of training programs to educate the user on how to apply these systems. This introduction will also require a higher level of expertise and knowledge.

REFERENCES

1. G.V. Hadjisophocleous, N. Bénichou and A.S. Tamin, "Literature review of performance-based codes and design environment", Journal of Fire Protection Engineering, Vol. 9, No. 1, pp. 12-40 (1998).
2. T. Ogawa, "The development process of a performance-based building code in Japan", Proceedings of the Global Building Model in the Next Millenium, Building Control, International Convention, 12-15 April, Melbourne, Australia, pp. 33-36 (1999).
3. Canadian Commission on Building and Fire Codes, Draft strategic plan final report of the CCBFC Strategic Planning Task Group, National Research Council of Canada, September (1994).
4. National Building Code of Canada, Canadian Commission on Building and Fire Codes, Institute for Research in Construction, National Research Council of Canada, Ottawa (1995).
5. Canadian Commission on Building and Fire Codes, Towards an improved code development system for Canada, Final report of the Joint CCBFC/PTCBS Task Group on the Code Review and Development Process, November (1998).
6. M. Law, "Fire safety design practices in the United Kingdom – New regulations", Proceedings of the Conference on Fire safety Design in the 21st Century, Worcester Polytechnic Institute, 8-10 May, Worcester, MA, USA (1991).
7. Draft British Standard Code of Practice for The Application of Fire Safety Engineering Principles to Fire Safety in Buildings, BSI Standards, Panel FSM/-/5 and Technical Committee FSM/24 Fire Safety Engineering, London, UK, June (1994).
8. G.P. Larsen, Nordic Model Performance Code, 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, 30 August - 1 September, Espoo, Finland (1993).
9. O. Berge, "Performance-based codes – the need for quality systems, qualifications of designers and contractors and new procedural rules in building control to ensure compliance", A presentation on the New Norwegian Legislation System,

Proceedings of the Global Building Model in the Next Millenium, Building Control, International Convention, 12 – 15 April, Melbourne, Australia, pp. 24-32 (1999).

10. V. Beck, "Performance-based fire engineering design and its application in Australia", Proceedings of the 5th International Symposium on Fire Safety Science, pp. 23-40 (1997).

11. A.H. Buchanan, "Fire engineering for a performance-based code", Fire Safety Journal, Vol. 23, pp. 1-16 (1994).

12. C.A. Caldwell, A.H. Buchanan and C.M. Fleischmann, "Documentation for performance-based fire engineering design in New Zealand", Journal of Fire Protection Engineering, Vol. 10, No. 2, pp. 24-31 (1999).

13. A.H. Buchanan, "Implementation of performance-based fire codes", Fire Safety Journal, Vol. 32, No. 4, pp. 377-383 (1999).

14. A.H. Buchanan (editor), Fire engineering design guide, Centre for Advanced Engineering, University of Canterbury, New Zealand, July (1994).

15. H.E. Nelson, "The GSA's systems approach to building protection", Presented at the NFPA annual meeting, Philadelphia, May (1972).

16. The Inter-jurisdictional Regulatory Collaboration Committee, Guidelines for the introduction of performance based building regulations (Discussion paper), May (1998).

17. R.W. Bukowski, F.B. Clarke, J.R. Hall Jr., and S.W. Stiefel, Fire risk assessment method: Description of methodology, National Fire Protection Research Foundation, Quincy, MA, July (1990).

18. P.J. DiNenno (editor-in-chief), SFPE Handbook of Fire Protection Engineering, 2nd edition, Society of Fire Protection Engineers, Boston, MA (1995).

19. R.W. Fitzgerald, "An engineering method for translating fire science into building design", International Symposium and Workshops on Engineering Fire Safety in the Process of Design: Demonstrating Equivalency, Proceedings Part 2, CIB W14: Fire Safety Engineering, 13-16 September, University of Ulster at Jordanstown, Antrim, Northern Ireland, pp. 39-70 (1993).

20. R.L.P. Custer and B.R. Meacham, Introduction to performance-based fire safety, National Fire Protection Association, Quincy, MA (1997).

21. Society of Fire Protection Engineers and National Fire Protection Association, SFPE engineering guide to performance-based fire protection analysis and design of buildings, Fire Protection Association, Quincy, MA (2000).

22. International Standard ISO 6241, Performance standards in building - principles for their preparation and factors to be considered, 1st edition, International Organization for Standardization, Switzerland (1984).

23. CIB report, Working with the performance approach in building, Publication 64, International Council for Building Research Studies and Documentation, Rotterdam, January (1982).

24. G.V. Hadjisophocleous, and N. Bénichou, "Performance criteria used in fire safety design", Automation in construction, Elsevier Science, Vol. 8, pp. 489-501 (1999).

25. Australian Fire Engineering Guidelines, 1st edition, Fire Code Reform Centre Ltd., Sidney, Australia (1996).

26. D. Yung, and V.R. Beck, Building fire safety risk analysis, SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, pp. 5-95 - 5-101 (1995).

27. V.R. Beck, and D. Yung, "The development of a risk-cost assessment model for the evaluation of fire safety in buildings", Proceedings of the 4th International Symposium on Fire Safety Science, 13-17 June, Ottawa, Canada, pp. 817-828 (1994).

28. G.V. Hadjisophocleous and D.A. Torvi, "Development of a fire risk assessment computer model for light industrial buildings", Canadian Society of Mechanical Engineering (CSME) Forum, Ryerson Polytechnic University, Toronto, ON, Vol. 3, pp. 305-310 (1998).

29. D. Yung, G.V. Hadjisophocleous and G. Proulx, "Modelling concepts of the risk-cost assessment model FiRECAM and its application to a Canadian government office building", Proceedings of the 5th International Symposium on Fire Safety Science, 3-7 March, Melbourne, Australia, pp. 619-630 (1997).