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THE EVOLUTION OF PERFORMANCE-BASED CODES AND FIRE SAFETY DESIGN METHODS

Brian J. Meacham
Society of Fire Protection Engineers
7315 Wisconsin Avenue
Bethesda, MD 20814

U.S. Department of Commerce
Technology Administration
National Institute of Standards and Technology
Gaithersburg, MD 20899

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U.S. General Services Administration
David J. Barram, *Administrator*
Public Building Service
Robert A. Peck, *Commissioner*
Washington, DC 20405

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*
Gaithersburg, MD 20899

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<u>Notice</u>

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The Evolution of Performance-Based Codes and Fire Safety Design Methods

Prepared for the
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Brian J. Meacham, P.E.,
Technical Director
Society of Fire Protection Engineers
One Liberty Square
Boston, MA 02109

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Foreword

This document provides an overview of the evolution of performance-based building codes and performance-based fire safety analysis and design methods. It was developed during the period of September 1995 through August 1996 as part of the National Institute for Standards and Technology, Building and Fire Research Laboratory, Grant No. 60NANB5DO138: Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States. Section 2 provides a chronological overview of the evolution of performance-based codes and performance-based fire safety analysis and design methods from the 1970s through the present. Sections 3 through 5 then detail the efforts undertaken in both code development and analysis and design method development during the 1970s, 1980s and 1990s respectively. The summary provides a list of analysis and design methods by type, and provides some thoughts on where future effort might be beneficial. Although sufficient detail is provided for the reader to gain an understanding of the fundamental principles behind the various codes, fire safety analysis methods, and fire safety design methods in use or in development as of July 1996, it is highly recommended that the referenced documents be consulted for more detailed information.*

* This report is a reprint of a document originally published by the Society of Fire Protection Engineers in August 1996. Although minor editorial modifications have been made, no updates have been included to reflect those advances in the areas of performance-based codes and fire safety design methods that have been made since 1996.

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The author would also like to express his sincere appreciation and indebtedness to Richard Custer, with whom he has worked for several years on the concept for performance-based fire safety analysis and design outlined in Section 5.8.2 of this document, and to his wife, Sharon Weber, who provided unquestioning support, without a complaint, throughout the development of this document.

Brian J. Meacham
Boston, Massachusetts, USA
August 1996

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1.0 Introduction

Although focused movement towards performance-based codes and standards is relatively recent in the United States, there have been objective- or performance-oriented regulations in various countries around the world for more than ten years. Beginning with the British[1] and Japanese[2] in the mid-1980s, and gaining worldwide attention through the Warren Centre Report[3] from Australia in the late 1980s, the move towards minimizing prescriptive constraints and maximizing design flexibility in building codes has become increasingly widespread. Arguably, Sweden[4] and the United States† can be included in this group of pioneers when one includes performance-based approaches to structural analysis and design.

The focus of this text, however, is strictly that of regulations, analysis and design methodologies related to fire and life safety. Within this narrow focus alone, there are currently no less than thirteen countries [Australia, Canada, Finland, France, Great Britain (England and Wales), Japan, The Netherlands, New Zealand, Norway, Poland, Spain, Sweden, and the United States] and two international organizations [the International Organization for Standardization (ISO) and the International Council for Building Research and Documentation (CIB)] using or actively developing performance-based codes‡ and the engineering tools and methodologies required to design fire-safe buildings within that form of regulatory structure.[5] The purpose of this chapter is to present an overview of the research and development efforts that have taken place with regard to regulations, analysis and design methodologies related to fire and life safety over the past twenty years.

2.0 Chronological Overview

The concepts of performance-based regulations and of engineered approaches to building fire safety have existed for several years. In fact, the concept has not changed dramatically since the introduction of the early fire safety engineering approaches of the 1970s. However, the availability of many more engineering tools and the evolution of performance-based building and fire regulations in many countries has resulted in increased interest in performance-based building fire safety design.

The purpose of this document is to acknowledge the pioneering efforts in the area of performance-based fire safety design, provide the background from which most of today's efforts evolved, and provide an overview of the approaches currently in use. Due to the magnitude and pace of effort worldwide, this document does not claim to be complete or comprehensive. Rather, this document provides the basis of many current efforts, including the approach described later in this text. Accordingly, it should not be assumed that those methodologies referenced are more significant that others that are not discussed (e.g., much of the discussion relates to material readily available in english-language publications). Table 1 provides a limited chronological overview of events influencing the development of performance-based codes and fire safety design approaches.

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† The model codes in the United States use performance objectives for structural and earthquake design, with design guidance developed by such organizations as the American Society of Civil Engineers (ASCE) and the Structural Engineers Association of California (SEAOC).

‡ For simplification purposes, the term performance-based code will be used throughout this text as a general term that encompasses performance-based, objective-based and functional codes.

Table 2-1. Chronological Listing of Events Influencing the Development of Performance-Based Codes and Fire Safety Design Approaches.

Year	Development and Country
1971	General Services Administration (GSA) hosts international conference on fire safety in high rise buildings (U.S.)[6,7]
1972	GSA publishes Building Safety Criteria, Appendix D, Interim Guide for Goal-Oriented Approach to Building Fire Safety (U.S.)[8]
1973	National Fire Protection Association (NFPA) Technical Committee on Systems Concepts for Fire Protection established (U.S.)[9]
1974	Fitzgerald et. al. begin development of the Anatomy of Building Firesafety (U.S.)[10]
1975	National Academy of Science publishes "Program for Developing and Implementing a New Approach to Designing for Fire Safety in Buildings" (U.S.)[11]
1976	Harmathy publishes "Design Approach to Fire Safety in Buildings" (Canada)[12]
1979	Seminal research undertaken by Vaughan Beck into risk assessment modeling (Australia)[13]
1979	Kobayshi publishes "A Methodology for Evaluating Fire/Life Safety Plannings of Tall Buildings" (Japan)[14]
1980	Society of Fire Protection Engineers (SFPE) Symposium on Systems Methodologies and some Applications (U.S.)[15]
1980	SFPE/National Bureau of Standards (NBS) Workshop on Engineering Applications of Fire Technology (U.S.)[16]
1981	NFPA Technical Committee on Safety to Life publishes the Fire Safety Evaluation System for Health Care Facilities (U.S.)[17]
1982-87	Ministry of Construction undertakes project on the Development of the Fire Safety Design Method (Japan)[2]
1985	The Building Regulations are published for the first time as a performance-based document (U.K.)[1]
1986	SFPE sponsors symposium on "Quantitative Methods for Life Safety Analysis" (U.S.)[18]
1986	The National Fire Protection Research Foundation (NFPRF) and the National Bureau of Standards (NBS) undertake the National Fire Risk Assessment Project (U.S.)[19]
1987	Beck collaborates with the National Research Council Canada (NRCC) on fire risk assessment modeling (Australia and Canada)[13, 20, 21]
1987	SFPE sponsors symposium on "Techniques of Quantitative Fire Hazard Analysis" (U.S.)[22]
1988	The SFPE Handbook of Fire Protection Engineering is published (U.S.)[23]

Year	Development and Country
1989	A report is issued by the Warren Centre for Advanced Engineering on their Fire Safety and Engineering project (Australia)[3]
1990	The National Building Fire Safety System Code (NBFSSC) drafted and introduced by the Building Regulation Review Task Force (BRRTF) (Australia)[24]
1990	The International Organization for Standardization (ISO) establishes a subgroup on the application of fire safety engineering principles to building fire safety (International)[25]
1991	Worcester Polytechnic Institute (WPI), the National Science Foundation (NSF) and the Society of Fire Protection Engineers (SFPE) sponsor Conference on Fire Safety Design in the 21st Century (U.S.)[26]
1991-93	Custer and Meacham develop course on performance-based design of fire detection systems for the SFPE (U.S.)[27]
1992	The performance-based New Zealand Building Code (and regulations) go into effect (New Zealand)[28]
1992	The Fire Administration Authorization Act of 1992 (Federal Fire Safety Act) goes into effect (U.S.)[29]
1992	The Electric Power Research Institute (EPRI) Publishes the document Methods of Quantitative Fire Hazard Analysis based on their developments of the Fire-Induced Vulnerability Evaluation (FIVE) Methodology (U.S.)[30]
1992-93	Draft British Standard Code of Practice for the Application of Fire Safety Engineering Principles to Fire Safety in Buildings developed (U.K.)[31]
1993	The International Council for Building Research and Documentation (CIB) establishes a task group on performance-based codes (TG11) (International)[32]
1994	CIB Working Commission 14: Fire (W14) establishes subgroups on Engineering evaluation of building fire safety and computer fire model evaluation (International)[33]
1994	The Swedish Board of Building, Housing and Planning introduces building regulations with performance criteria (Sweden)[34]
1994	The Fire Engineering Design Guide published (New Zealand)[35]
1994	The Fire Code Reform Centre Ltd (FCRC) established (Australia)[36]
1994-95	Custer and Meacham develop course for SFPE on performance-based design for fire protection engineers (U.S.)[37]
1995	The Australian Building Codes Board (ABCB) drafts the Performance Building Code of Australia (Australia)[38]
1995	The Canadian Commission on Building and Fire Codes (CCBFC) introduces plan to convert building code from prescriptive to objective-based (Canada)[39]
1995	The Nordic Committee on Building Regulations publishes *Performance Requirements for Fire Safety* and *Technical Guide for Verification by Calculation*[40]

Year	Development and Country
1995	The FCRC publishes interim Fire Engineering Guidelines (Australia)[41]
1995	The NFPA publishes concept for transition of NFPA codes and standards from prescriptive to performance-based (U.S.)[42]
1995	The Ministry of Construction undertakes new project for performance-based building code (Japan)[43]
1995	SFPE undertakes project to identify framework for performance-based fire safety design in the United States. (U.S.)[44]

3.0 Developments in the 1970s

The 1970s saw the beginnings of a dramatic shift in thinking from the traditional "complies with the code/does not comply with the code" approach to a "systems" approach for evaluating and designing building fire safety measures. During this period, a few visionaries began demonstrating that engineers can view the building and the fire as integral components of a single system, and that by evaluating or designing individual components without regard to the system, potentially severe shortcomings in the design could result.

3.1 Early Systems Approaches for Fire Safety

In April 1971, the General Services Administration (GSA) Public Buildings Service convened an International Conference on Fire Safety in High-Rise Buildings in Airlie, Virginia. A systems approach to fire safety in buildings was one area of discussion. In the resulting conference report, delegates described the fundamental elements needed in a systems approach for fire safety in high-rise buildings.[6]

Later that year, Harold E. Nelson, then Director of Accident and Fire Prevention for the GSA, was faced with selecting fire safety requirements for the Seattle Federal Building. While no formalized systems approach had yet been developed for fire safety design, Nelson, with the input from the recent Airlie House Conference, undertook a systematic approach to the fire safety analysis. His approach took the form of a fire safety systems guide that qualitatively summarized the fire safety elements of the Seattle Federal Building. This concept was presented when the Airlie House Conference was reconvened in Washington, D.C. in October 1971.[7] A second paper presented at the conference, by Irwin A. Benjamin of the National Bureau of Standards (NBS), introduced an event logic diagram of fire safety elements essential to building fire safety. Taken together, these two documents formed the basis of a comprehensive systems approach to analyzing building fire safety.

In 1972, the GSA and the NBS, expanding on the efforts of Nelson and Benjamin, jointly developed an event logic diagram which showed alternative approaches to achieving building fire safety. After several revisions, this tree eventually became the basic reference guide of the GSA's goal-oriented systems approach to building fire safety. This document, commonly referred to simply as *Appendix D*,[8] became the basic document for describing a systems approach to building fire safety design.

The major features of Appendix D include:

- A concept of relative risk (the absence of risk is not feasible).
- Management goals as described in the context of acceptable levels of risk.
- Workable components of a fire safety system that can be adapted to any building.
- An event logic tree expressing relationships among the different system components.
- A method of calculation enabling the performance of an alternative fire safety system to be compared.
- The use of probability to describe fire safety performance.

Following the publication of *Appendix D*, activities relating to systems approaches to building fire safety expanded considerably. One direct result was the formation of the National Fire Protection Association Technical Committee on Systems Concepts for Fire Protection. This committee's first action was to publish an event logic tree related to fire safety in 1973.[45] This tree was then updated in 1974 to better relate the various components of building fire safety.[46] Modified over time, the final version of the event tree can be found in NFPA 550, *Guide to the Fire Safety Concepts Tree*.[47] A portion of the Firesafety Concepts Tree is provided in Figure 1.

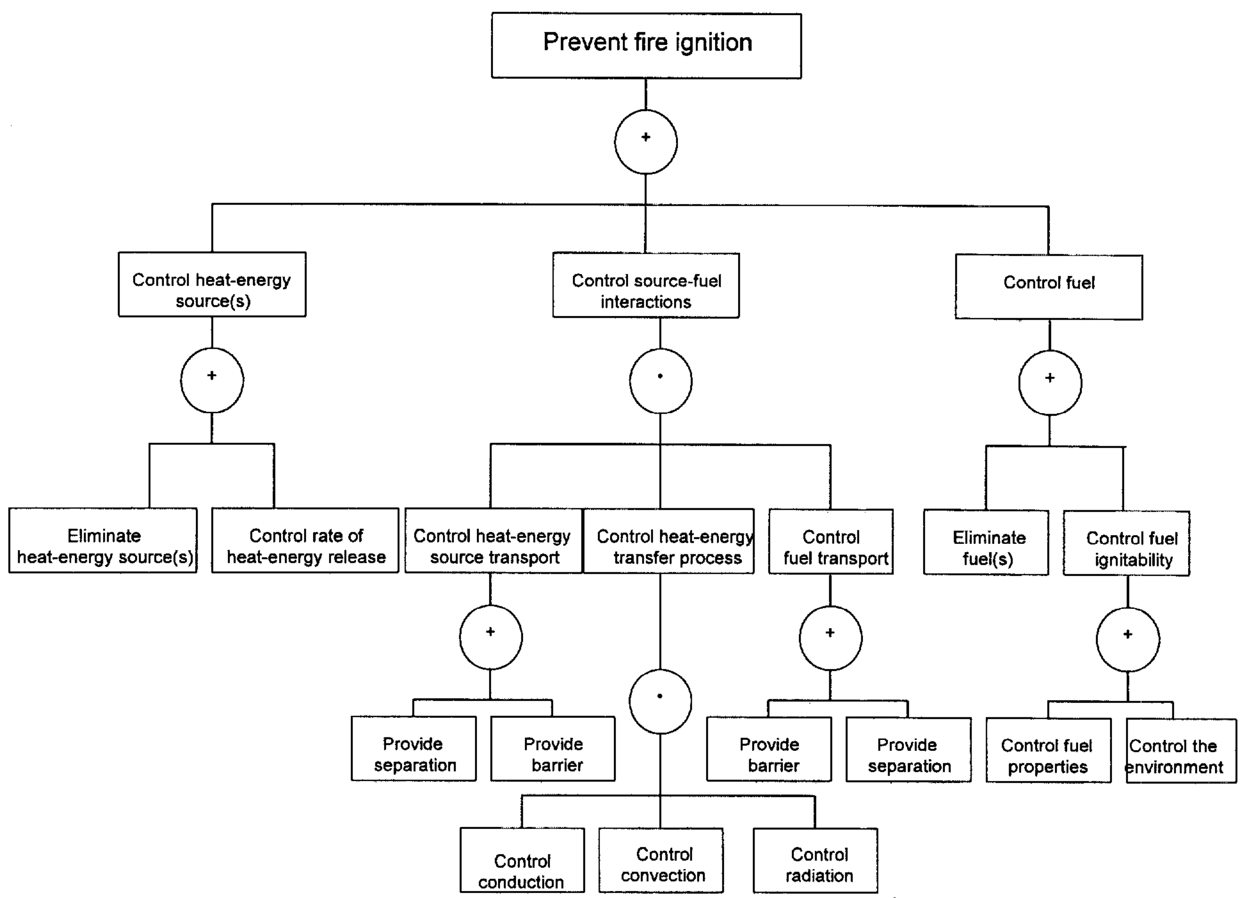

Figure 1 - Prevent Ignition branch of the Firesafety Concepts Tree (from figure 3-2, NFPA 550, *Firesafety Concepts Tree*, 1986)

The development and teaching of a five-day short course on a systems approach to fire safety also followed the publication of *Appendix D.* Rexford Wilson and Robert Fitzgerald taught the first course, the *Anatomy of Building Firesafety*, at the University of Wisconsin in June 1974.[10] Over the next few years, Fitzgerald and others modified the approach to address both theoretical and practical aspects in fire safety analysis. By the end of the 1970s, network models had been adapted to the framework Fitzgerald had developed. The network models replaced the traditional fault tree structure.[48,49] Fitzgerald found the network models to be useful as a visual indication of the sequential dependency of certain events and of the interrelationship of various parts of the system.

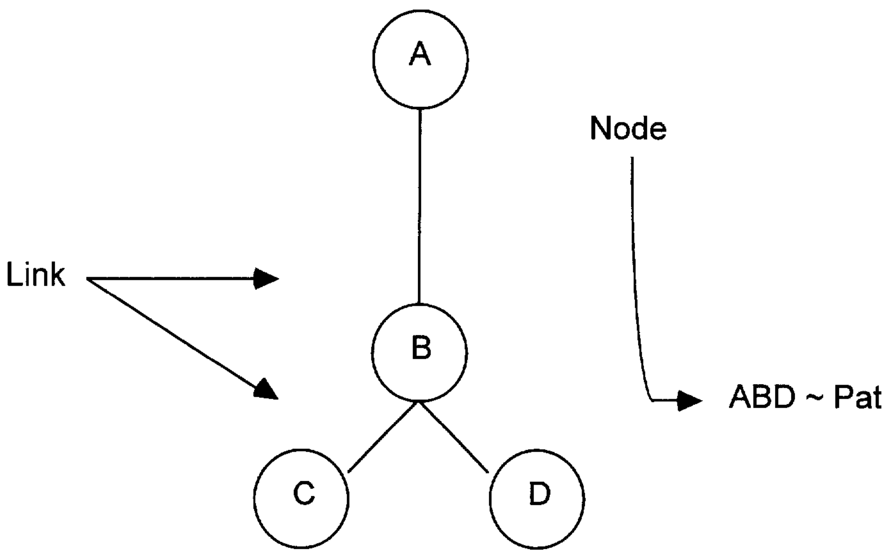

Figure 2 - Simple Network Diagram

Network models are simply graphical representations of paths or routes, by which objects, energy, information or logic may flow, or move, from one point to another.[50] A simple network diagram is shown in Figure 2. The various (information) points in a network model are called *nodes* (e.g., A, B, C and D), and the connections between nodes are called *links* (e.g., AB, BC and BD). A sequence of links connecting two nodes (and usually passing through others) is called a *path* (e.g., ABD). Network diagrams are useful in that they provide a qualitative representation of the structure of a problem or a system.

3.2 The Building Fire Safety Evaluation Method (BFSEM)

Fitzgerald later expanded on the fundamental concepts of Nelson and of the *Anatomy of Building Firesafety* and developed the *Building Firesafety Evaluation Method* (BFSEM).[51,52] The BFSEM uses a structured framework to guide the process of performance evaluation. With this method, the user can evaluate the likelihood of ignition, fire growth, and fire spread through an existing building or new building for which plans have been developed, focusing on such factors as fuel loading, occupancy characteristics, active fire protection features and structural features. Using network diagrams, the user evaluates such factors as ignition potential, fire growth potential within the compartment of origin, barrier performance, fire spread beyond the compartment of origin, and occupant safety. The user can assign subjective probabilities, based on experience and engineering judgment, or statistical data when available, to estimate the likelihood of each event occurring (the outcome is the likelihood that any event will or will not occur). Two network diagrams from the BFSEM are shown in Figure 3.

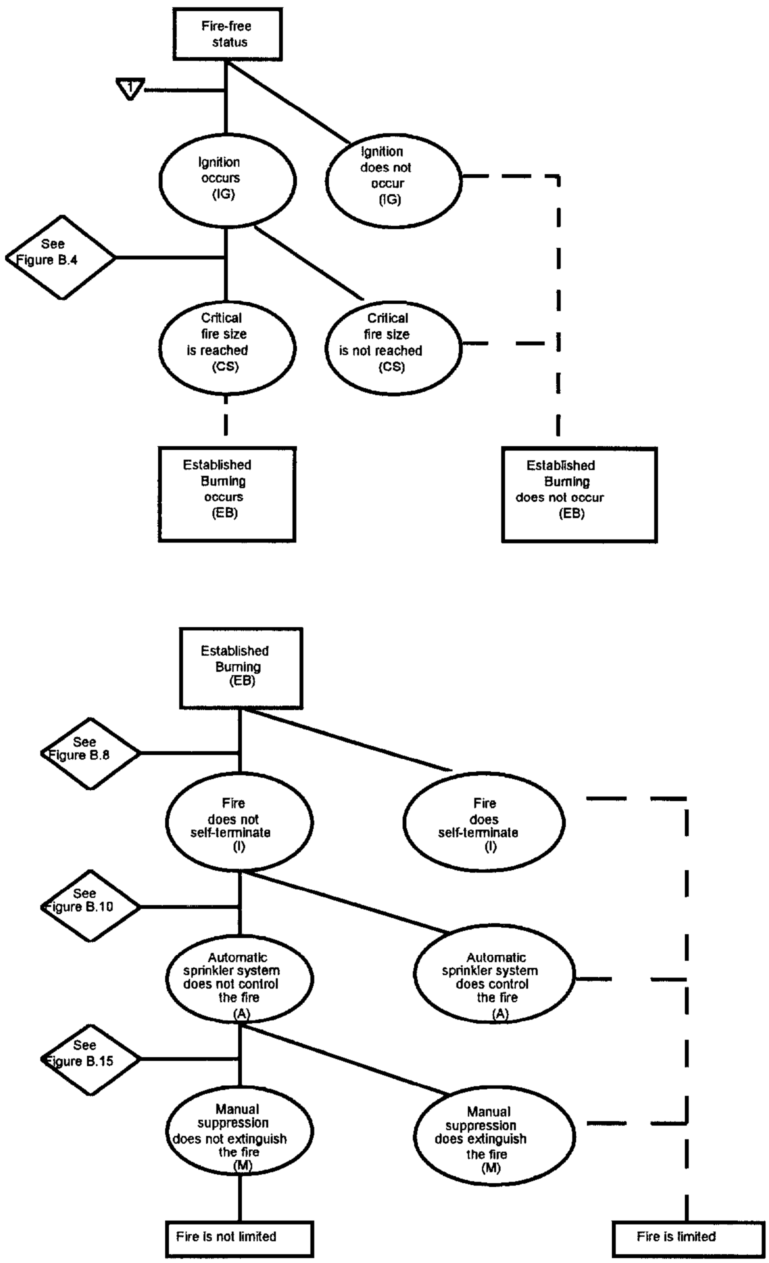

Figure 3 - Examples of BFSEM Network Diagrams[51]

Within the BFSEM process, fire related factors, such as fuel load and arrangement, and fire protection features, such as automatic and manual fire detection and suppression (including fire department response), integrity of barriers and operation of emergency systems, are evaluated based on the user's judgment as to how the fire will develop and spread (which can be supported by deterministic calculation methods when desired). In attempting to determine the likelihood of successful control of a fire by sprinkler activation, for example, one must evaluate the ability of the fire to grow to a sufficient size to activate the sprinkler and then evaluate the likelihood that the sprinkler can control the fire. The latter action may involve an evaluation of the sprinkler system (or design), the water supply, and the reliability of the system operation (statistical data, where available, can be added to support this stage of the evaluation).

The basic concepts of the BFSEM are as follows. All buildings are assemblies of spaces and barriers. A clear identification is made for the specific spaces and barriers that are used for a particular building performance analysis. This is defined as *space-barrier organization.* The fire itself is separated into two components: flame/heat and smoke/gas. This is done because each component impacts the building, its occupants and its contents at different speeds and in different ways.

Within the BFSEM, ignition is defined as self-sustained burning of an item, typically when the first small flame appears (smoldering is defined to occur before ignition). If the ignited material is expected to continue burning (i.e., is not expected to self-terminate), the fire is then classified as having attained *established burning* (i.e., sufficient fuel is present and arranged so as to continue burning if adequate ventilation is present). Assuming no intervention is taken, the fire then grows to full room involvement (i.e., the condition where the surfaces of all combustibles in the room are burning). Full room involvement can be assumed when flashover occurs. (Flashover is the very rapid ignition of collected fire gases in a room.) After full room involvement commences, the fire will burn for an extended period of time until the fuel is nearly consumed, or until fire suppression is successful in extinguishing the fire. The literature often describes this stage of the fire as a "post flashover" or "fully developed" fire.

In the BFSEM, the term *barrier performance* is used to describe a barrier's ability to prevent fire propagation, where a barrier is defined as any surface that will delay or prevent an ignition into an adjacent space. At any time during the fire, a barrier can be considered as being successful (if it does not permit any ignition to occur in the adjacent space), as having a small failure (e.g., a crack) or as having a massive failure (e.g., door open, large hole, etc.). The *limit of flame movement* is the extent to which the fire spreads before it is terminated. (The term "limit" may be applied to the extent of fire spread either in a space or in a building.)

Evaluation of building performance using the BFSEM is accomplished by applying the above concepts to the following areas: *prevention*, *flame/heat analysis* (the ability of the building to limit the fire in its spaces and barriers through active and passive fire defenses), *smoke/gas analysis* (the ability of the building to maintain tenable conditions in selected spaces for prescribed time durations), *structural frame analysis* (the ability of the structural frame to avoid unacceptable deformation or collapse for a fire that is not limited), and *people movement analysis* (the time required for building occupants to move within the building or to locations of safety).

Application of the BFSEM provides a comprehensive method for identifying factors that affect the fire safety performance of a building. The method has been adapted by the U.S. Coast Guard as their Ship Fire Safety Engineering Methodology (SFSEM).[53] It is a valuable tool and fits quite well with the framework for performance-based analysis and design described in this book.

3.3 Fire Safety Evaluation System (FSES)

Another approach that resulted from the early GSA *Appendix D* work is the Fire Safety Evaluation System (FSES) used in NFPA 101A, *Guide on Alternative Approaches to Life Safety*[54] (referred to hereafter as 101A). Although sometimes referred to as a performance-based approach, the FSES is in fact "a schedule approach to determining equivalencies to the NFPA 101 *Life Safety Code*®[55] for certain institutional occupancies."[56] The FSES provides a uniform method of comparing fire safety measures in a number of facilities against the level of fire safety provided by the *Life Safety Code*. At present there are FSES schedules for health care, detention and correction (prisons), board and care and business occupancies as defined by the <u>Life Safety Code</u> (each schedule varies slightly based on the occupancy).

In general, an FSES consists of a variety of fire safety parameters (such as construction, hazardous areas, manual fire alarms, automatic detection systems, automatic sprinkler systems and the like) for which designated point values have been provided in the 101A. During a building evaluation, the evaluator will determine what fire safety measures are present, and assign appropriate point values in accordance with 101A. If the point total equals or exceeds the predetermined total designated in the Code, then the fire safety is deemed to be equivalent to that provided in NFPA 101. In some cases, such as for health care facilities, there are also risk parameters for patient mobility, patient density, fire zone location, ratio of patients to attendants, and average patient age. Examples of FSES parameter values for a health care occupancy are shown in Figures 4 and 5.

Risk Factor Values

Risk Parameters

1. Patient Mobility (M)

Mobility Status	Mobile	Limited Mobility	Not Mobile	Not Movable
Risk Factor	1.0	1.6	3.2	4.5

2. Patient Density (D)

# of Patients	1-5	6-10	11-30	>30
Risk Factor	1.0	1.2	1.5	2.0

3. Zone Location (L)

Floor	1st	2nd or 3rd	4th to 6th	7th & above	Base-ments
Risk Factor	1.1	1.2	1.4	1.6	1.6

4. Ratio of Patients to Attendants (T)

Patients/ Attendant	1-2 /1	3-5 /1	6-10 /1	>10 /1	One or† more /None
Risk Factor	1.0	1.1	1.2	1.5	4.0

5. Patient Average Age (A)

Age	Under 65 Years and Over 1 Year	65 years and Over 1 Year and Younger
Risk Factor	1.0	1.2

†A risk factor of 4.0 is charged to any zone that houses patients wi thout any staff in immediate attendance.

Figure 4 - Occupancy Risk Parameter Factors (from Table 3-1 of the Fire Safety Evaluation System)[54]

Safety Parameters	Parameter Values						
1. Construction	Combustible Types III, IV, and V				Noncombustible Types I and II		
Floor or Zone	000	111	200	211 + 2HH	000	111	222, 322, 433
First	-2	0	-2	0	0	2	2
Second	-7	-2	-4	-2	-2	2	4
Third	-9	-7	-9	-7	-7	2	4
4th and Above	-13	-7	-13	-7	-9	-7	4
2. Interior Finish (Corridors and Exits)	Class C	Class B	Class A				
	- 5 (0)[f]	0 (3)[f]	3				
3. Interior Finish (Rooms)	Class C	Class B	Class A				
	- 3 (1)[f]	1 (3)[f]	3				
4. Corridor Partition/Walls	None or incomplete	< 1/3 hour	≥1/3 < 1 hr	≥1 hr			
	-10 (0)[a]	0	1 (0)[a]	2 (0)[a]			
5. Doors to Corridor	No Door	<20 min FPR	≥ 20 min FPR	≥ 20 min FPR and Auto Clos.			
	-10 (0)	0	1 (0)[d]	2 (0)[d]			
6. Zone Dimensions	Dead End			No Dead Ends > 30' and Zone Length is:			
	>100'	>50' to 100'	30' to 50'	>150'	100' to 150'	<100'	
	-6 (0)[b]	-4 (0)[b]	-2 (0)[b]	-2	0	1	
7. Vertical Openings	Open 4 or More Floors	Open 2 or 3 Floors	Enclosed with Indicated FRR				
			<1hr	≥1< 2 hr	≥2		
	-14	-10	0	2 (0)[e]	2 (0)[e]		
8. Hazardous Areas	Double Deficiency		Single Deficiency		No Deficiencies		
	In Zone	Outside Zone	In Zone	Outside Zone			
	-11	-5	-6	-2	0		
9. Smoke Control	No Control	Smoke Barrier Serves Zone	Mechanically Assisted Systems by Zone				
	-5 (0)[c]	0	3				
10. Emergency Movement Routes	<2 Routes		Multiple Routes				
		Deficient	W/O Horiz. Exits	Horiz. Exits	Direct Exits		
	-8	-2	0	1	5		
11. Manual Fire Alarm	No Man. Alarm	Manual Fire Alarm					
		W/O FD Conn.	With FD Conn.				
	-4	1	2				
12. Smoke Detection and Alarm	None	Corridor Only	Rooms Only	Corridors and Habitable Spaces	Total Spaces in Zone		
	0 (3)[g]	2 (3)[g]	3 (3)[g]	4	5		
13. Automatic Sprinklers	None	Corridors and Habitable Spaces	Entire Building				
	0	8	10				

NOTES: [a]Use (0) where Parameter 5 is -10
[b]Use (0) where Parameter 10 is -8
[c]Use (0) on floor with less than 31 patients (existing building only)
[d]Use (0) where Parameter 4 is -10
[e]Use (0) where Parameter 1 is based on first floor zone or on an unprotected type of construction (columns marked "U")
[f]Use () if the area of Class B or C interior finish in the corridor and exit or room is protected by automatic sprinkler and Parameter 13 is 0
[g]Use this value in addition to Parameter 13 if entire zone is protected with quick response sprinklers

Figure 5 - Safety Parameter Values (from Table 3-4, NFPA 101A, 1995)

It should be noted that the values for both the fire safety parameters and the risk parameters were developed from the "experienced judgment of a group of fire safety professionals and represent the opinions of that panel of experts."[56] For this reason, there is no definitive process for validating these values. Without such a process, it is difficult to transfer the concepts to determine equivalency to other codes.

3.4 Risk Assessment Modeling

While efforts such as those by Fitzgerald et al. focused on the use of subjective probability, and the FSES more on equivalencies, a more traditional approach in probabilistic analysis can be traced back to research into risk assessment modeling by Vaughan Beck in 1979.[13] The intent of his research was to identify cost-effective building fire safety design solutions that achieved an acceptable level of occupant fire safety. To meet this objective, Beck developed a building fire safety system model that estimated the level of risk for the particular building being modeled. The resulting system model, which is based on stochastic state-transition models, is made up of several sub-models founded in part on various analytical and conceptual models of the 1970s.

> Stochastic is a statistical term pertaining to a process involving a randomly determined sequence of observations, each of which is considered as a sample of one element from a probability distribution. The rate of flame spread and fire growth and the response of individuals to fire alarm signals are examples of variables that can be considered stochastic in nature. In modeling one of these variables, the stochastic element may be introduced at any point in a model run so that the value of a variable at any time depends in some way on its previous value and a random component. Stochastic variation (state-transition) implies randomness as opposed to a fixed rule or relation in passing from one observation to the next in order.[57]

The risk assessment system model (top level) is founded on an event-based modeling approach wherein events are characterized in terms of discreet times and probabilities of occurrence. The risk assessment model is used to characterize the outcome of a fire growth and spread scenario in terms of times to reach untenable conditions using sub-systems (i.e., Nature of Occupancy, Fire Growth and Development, Smoke Management, Flame Management, Occupant Avoidance and Fire Fighting). [Note the similarity to the five-components of Fitzgerald's BFSEM: prevention, flame/heat analysis, smoke/gas analysis, structural frame analysis and people movement analysis.] The consequences are then expressed in terms of the number of people exposed to the untenable conditions.

Beck's model assesses the fire safety performance of a specific fire safety design in terms of two decision-making parameters: *The Expected Risk to Life (ERL)* and the *Fire Cost Expectation (FCE)*.[13,20,21] The ERL is the expected number of deaths over the lifetime of the building divided by the total population of the building and the design life of the building. The FCE is determined as the total fire cost for the building including the capital cost per passive and active fire systems, maintenance costs for the active fire protection systems and the expected losses resulting from fires in the building. In the model, the ERL is a quantitative measure of the risk to life from all probable fires in the building given a particular fire safety system design; whereas the FCE quantifies the fire cost associated with that particular fire safety system design.

To calculate the expected risk to life and the fire cost expectation values, the model considers interaction between fire growth, fire spread, smoke movement, human behavior, the response of building systems and the response of a fire brigade. The simplified flow chart for this is shown in Figure 6. The model uses specified design fires to characterize the broad spectrum of fires that could be expected in reality. As Beck[13] has noted, due to the complexity and lack of sufficient understanding of fire phenomena and human behavior, certain conservative assumptions in approximations have been made in the mathematical modeling. As a result, the predictions made by the model should only be considered as approximate, and should not be used for absolute assessments, life risks or protection costs. For comparative or relative assessments, however, such as comparing a proposed design to a code-conforming design, the model can be considered much more reliable and effective.

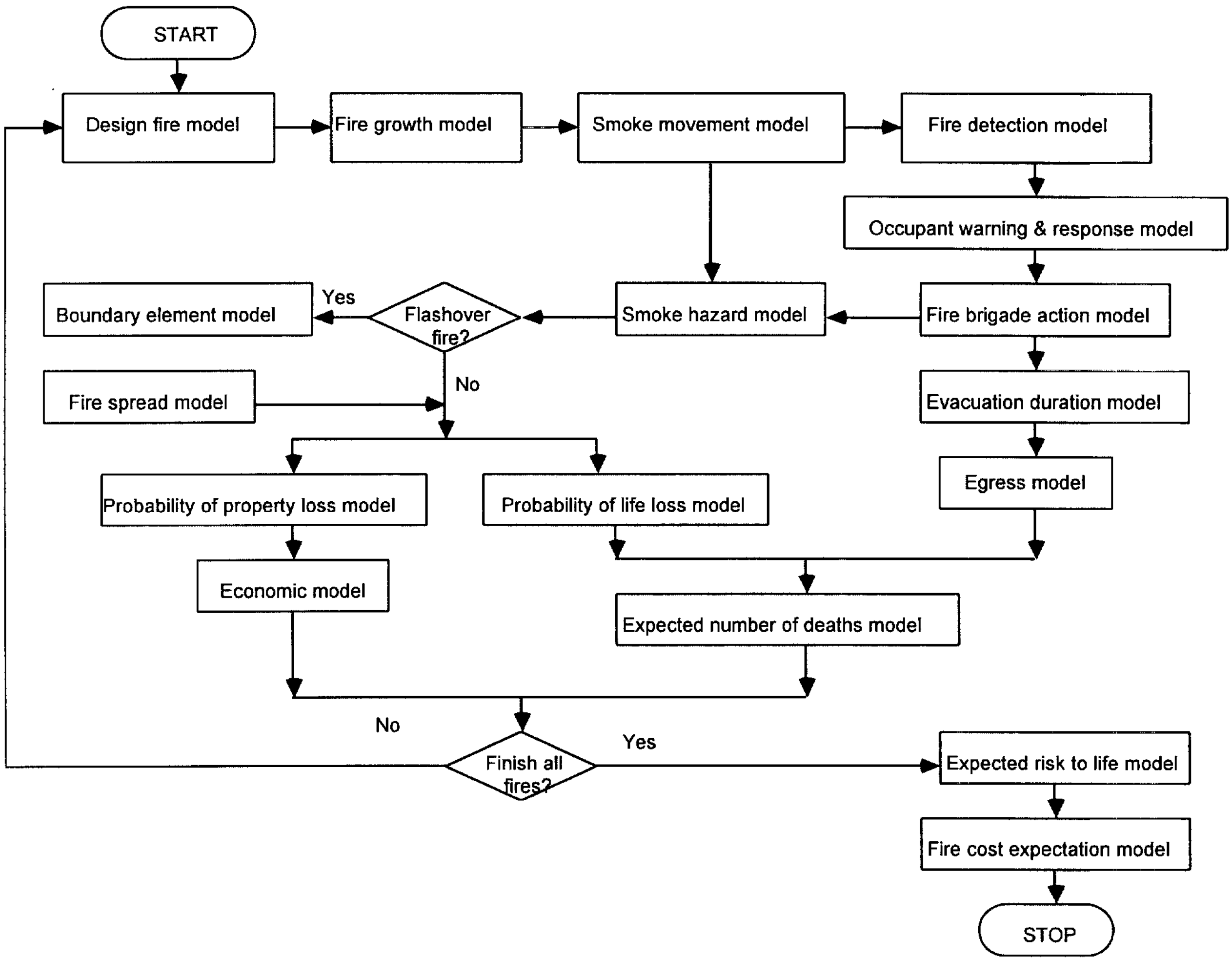

Figure 6 - Flow Chart for Beck's Risk-Cost Assessment Method

4.0 Developments in the 1980s

4.1 The United Kingdom

Until 1985, the building regulations for England and Wales were largely prescriptive and rather restrictive. The reasons for this are easy to understand. Beginning with the Fire of London in 1666, regulations were set forth to help limit the spread of fire between buildings and prevent a similar loss from occurring. During the years that followed, the regulations were expanded and modified to reflect lessons learned from fatal fires, changes in building technology, and the like. However, by 1976, these regulations had grown in size to a total of 307 pages, which as Margaret Law[58] writes, "were very prescriptive and understood mainly by lawyers."

In an attempt to increase flexibility in design, and produce a more intelligent system, a reform of the building regulations was undertaken in the late 1970s and early 1980s. The result was dramatic. With its publication in 1985, the *Building Regulations* had been reduced from 307 pages to only 23 pages, while still covering requirements for Structure, Fire, Site Preparation and Resistance to Moisture, Toxic Substances, Resistance to the Passage of Sound, Ventilation, Hygiene, Drainage and Waste Disposal, Heat Producing Appliances, Stairways, Lamps and Guards, Conservation of Fuel and Power, and Facilities for Disabled People.

This was made possible, in part, by using functional, or performance wording, instead of prescriptive requirements. For example, the internal fire spread requirements in the regulations, as related to surface spread of flame, read as follows:[1]

> **Internal fire spread (surfaces)**
>
> **B2.** In order to inhibit the spread of fire within the building, surfaces of materials used on walls and ceilings -
> (a) shall offer adequate resistance to the spread of flame over their surfaces; and
> (b) shall have, if ignited, a rate of heat release which is reasonable in the circumstances.

Similarly, the internal fire spread requirements for the structure were also functional, and open to wide interpretation:

> **Internal fire spread (structure)**
>
> **B3.** - (1) The building shall be so constructed that, in the event of fire, its stability will be maintained for a reasonable period.

Terms such as "adequate resistance" and "reasonable under the circumstances" are open to broad interpretation, and often depend upon the user's specific design objectives and the purpose(s) for which a particular structure is intended. As such, the objectives might well be construed to be "in the eye of the beholder."

This radical change in regulatory language led to the opportunity for engineers to demonstrate compliance using "acceptable engineering methods." However, due to the complexities in gaining acceptance for methods that may not be understood or agreed to by all, many designers and engineers chose to rely on the prescriptive guidance provided in the "Approved Documents" and a series of British Standards (BS 5588 series).[58]

The fire safety engineering community recognized this conflict in ideals and in the early 1990s set out to develop a set of guidelines, or in British terms, a code of practice, that would promote the use of fire safety engineering principles in building design. This will be discussed further in Section 5, Developments in the 1990s.

4.2 Japan

The regulatory situation was similar in Japan. Since 1950, Japan had operated under a highly prescriptive building code system: the Building Standards Law. Although these regulations seemed adequate in providing an acceptable level of fire safety, by the early 1980s, the Japanese government also felt that they "incurred the undue increase of construction costs and restraint to building designs."[43]

Some of the drawbacks that were identified included inefficient and/or overlapping fire safety measures, limited flexibility in architectural design, difficulty in gaining approval to apply newly developed fire safety technologies, difficulty in understanding the actual level of fire safety, and a sense of general discouragement against improving the level of fire safety (i.e., no clear benefits to improve).

Recognizing this situation, the Building Research Institute (BRI) of the Ministry of Construction (MOC) embarked on a planned five-year research project beginning in 1982 to develop a performance-based design system that could be used as an alternate to the Building Standards Law. The intent was quite simple: develop a system in which it could be demonstrated that an alternative fire safety design is equivalent to the objectives of the Building Standards Law.[43, 59]

The first step in developing the performance-based design system was to identify the primary goals of the Building Standards Law in terms of the building fire safety design. These were identified as: preventing the outbreak of fire, protection of life, protection of property and protection of the public and public concerns outside of the building of fire origin (e.g., minimizing fire spread between buildings). To these, the goal of maintaining acceptable conditions for fire-fighter access and operations within the building during a fire was added.[59]

The system that was developed, "The Total Fire Safety Design System of Buildings,"[2,43,59] is composed of five sub-systems: Total Fire Safety, Prevention of Fire Outbreak and Spread, Smoke Control and Evacuation, Fire Resistance, and Fire Safety for Dwellings, each of which has four components: Fundamental Requirements, Technical Standards for Engineering Evaluation, Prediction Method of Relevant Fire Phenomena, and Concepts of Testing Methods.

The five primary sub-system categories are clear (e.g., Prevention of Fire Outbreak and Spread). The *technical standards* in each subsystem provide criteria for the evaluation of fire safety using calculation methods. These criteria are composed primarily of "standard conditions" to be assumed for the calculation of critical levels in terms of engineering properties (e.g., temperature, gas concentration and so forth). The *prediction methods* are "approved" methods for calculating these criteria (i.e., equations, correlations or models), and the *concepts of testing methods* provide 'acceptable' means of verification.

Although the system has its shortcomings, it has nevertheless resulted in a significant increase in the number of applications submitted to the Ministry of Construction for equivalencies to the Building Standards Law.[43]

Tanaka indicates the a significant shortcoming of this approach is its dependence on the Building Standards Law.[59] That is, the design approach can only be used under Article 38 of the Law for determining equivalencies, and can not stand alone as an independent performance-based fire safety design tool. To overcome this shortcoming and expand the application of performance-based fire safety design, the Ministry of Construction began a new project in the mid 1990s, "Development of Assessment Method of Fire Performance of Building Elements," to provide scientific and engineering support for the system (this project is not discussed in this text).[43]

4.3 United States

In the United States, the National Fire Protection Research Foundation (NFPRF) undertook the National Fire Risk Assessment Project in 1986.[19] The goal of this effort was to develop "an objective, comprehensive, generally applicable and widely recognized fire risk assessment methodology for products that go into buildings." This was a collaborative effort between the

National Institute of Standards and Technology (NIST), the NFPA Fire Analysis & Research Division, and the private consulting firm of Benjamin/Clarke Associates. This effort developed a method to quantify the fire risk associated with a specific class of products in a specified occupancy: *FRAMEworks*.

FRAMEworks is similar in many respects to the risk assessment model of Beck described earlier in this text. *FRAMEworks* combines a quantitative (fire modeling) method to evaluate specific products in specific fire scenarios with a statistical method of relating fire deaths to the specific scenarios in order to establish a death rate baseline for the scenarios. The impact of new or replacement products can then be evaluated against the baseline scenarios to determine if the risk is comparatively higher or lower with a change of product(s). The fundamental operation of *FRAMEworks* is illustrated in Figure 7.[19]

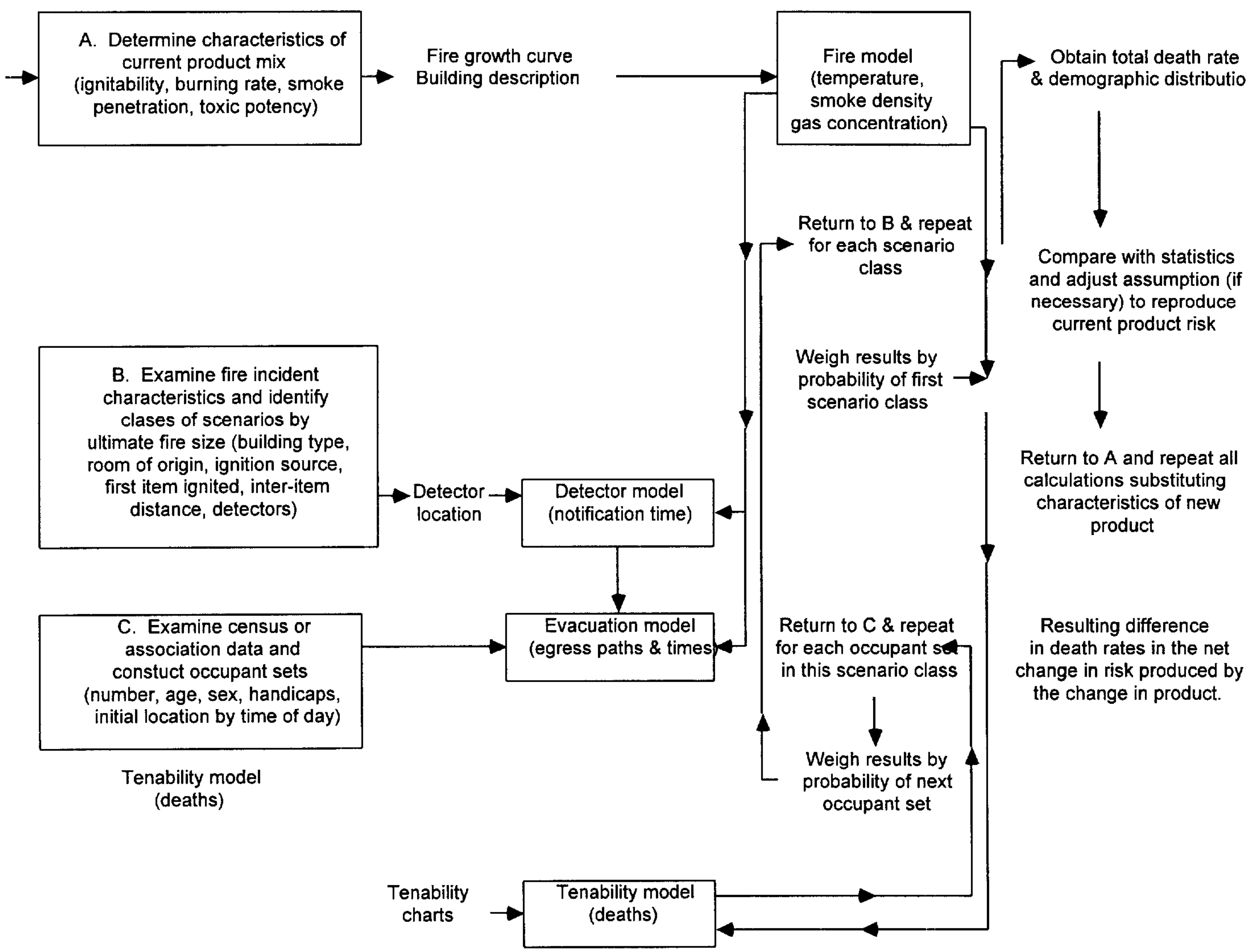

Figure 7 - Modeling Sequence to Compute Fire Risk in *FRAMEworks*

At about the same time as the NFPRF risk assessment project began, the Society of Fire Protection Engineers (SFPE) realized that practicing fire protection engineers needed fire science and engineering tools that could be readily used in the design office. To help address this need, the SFPE undertook development of the SFPE Handbook of Fire Protection Engineering:[23] a resource document consisting of fundamentals of fire science and engineering; analysis and design tools, methods and approaches; deterministic and probabilistic methods for hazard and risk analysis and more. When published in 1988 as the first engineering-oriented compilation of fire science and engineering tools and methods, the Handbook became a cornerstone in the application of engineered approaches to fire safety problems. For many, the Handbook was also a key reference document in the support of performance-based fire safety design.

4.4 Canada

While the NFPRF risk assessment project was underway in the United States, Australia's Vaughan Beck spent four months of 1987 on sabbatical at the National Research Council Canada following up on his initial efforts with the building firesafety risk assessment model discussed earlier.[13] Subsequently, the NRCC contracted with Beck to modify the model for application to Canadian high-rise apartment buildings.[20] Although these efforts resulted in a solid foundation for the model, several deficiencies remained, including the fact that the submodels used to estimate probabilities of smoke and flame spread were overly restrictive and did not consider time effects. Additional effort in the 1990s would address several of these concerns.

4.5 Australia: The Warren Centre Project

Following his sabbatical at NRCC, Beck returned to Australia and was appointed Visiting Professorial Fellow at the Warren Centre for Advanced Engineering at the University of Sydney in 1989 to lead a project on fire safety and engineering in Australia.[13] The Fire Safety and Engineering project, or Warren Centre project, pulled together some 70 project fellows from Australia's building, fire and research communities to discuss the need to base fire safety design on engineering technology.

The principal recommendations from the 1989 project were:[3,13]

- The current levels of fire safety in Australia should be maintained,
- Design for fire safety should be treated as an engineering responsibility rather than a matter for detailed regulatory control,
- Risk assessment models should be used as a basis for identifying cost-effective combinations for fire-safety sub-systems for building design,
- Designers should adopt appropriate fire safety engineering techniques for the design of fire safety systems in buildings,
- Fire engineering design courses and training strategies should be developed and implemented (up to and including post-graduate level), and
- A national strategy should be developed for research, development, application and education relevant to fire safety engineering design.

In developing these recommendations, the project participants also considered the economic losses associated with fire in Australia. At the time of the project, an estimated A$2 billion annually were attributed to losses and costs associated with building fires, fire protection and insurance in Australia.[13] However, it was also estimated that this figure could be reduced by at least A$250 million per year with the development and implementation of fire safety engineering technology and performance-based fire design codes.

Using the information contained in the *Warren Centre Report* as a base, the Building Regulation Review Task Force (BRRTF), which was established in 1989, developed the first draft of a performance-oriented building code entitled the National Building Fire Safety System Code (NBFSSC).[24] As Beck has written,[13] the objective of the NBFSSC was to provide flexible and technologically advanced procedures, based on risk assessment modeling, to achieve cost-effective building designs which conform to the fire safety levels implicit in the building regulations. This draft code would become a critical component in the development of the Performance Building Code Australia and the (Australian) Fire Engineering Guidelines in the 1990s.

5.0 Developments in the 1990s

5.1 Developments in the United Kingdom

The Building Code for England and Wales, which was modified to be performance oriented in 1985, was revised again in 1991.[60] One of the key additions to the 1991 version was the reference to the use of Approved Documents or alternative methods based on fire safety engineering principles in meeting the objectives of the regulations. Even with this change, many remain reluctant to seek alternative designs to the approved documents portion of the regulations. A primary reason for this reluctance is the lack of guidance, not only for fire safety engineers, but also for the building authorities who review the designs. To address this issue, the British Standards Institute (BSI) contracted a design team to develop a draft code of practice for the application of fire safety engineering principles to building fire safety design.

At the time of this text, the BSI is considering the resulting document, *The Application of Fire Safety Engineering Principles to Fire Safety in Buildings*,[31] as a British Standard Draft for Development. (As a result, details of the document that BSI is to release in 1996 are presently unavailable.) From published reports on the draft version, it appears that the document is a comprehensive, well structured and well documented source for providing guidance in the engineering and evaluation of building fire safety design.[61,62] The fundamental approach of the BSI draft for development document is much the same as the approach described under Section 5.6.1, efforts of the International Organization for Standardization (ISO), as the Global Information Bus and can be reviewed there. [Author's note: An early version of the BSI document was used as a basis for the ISO document referenced in Section 5.6.1. As the BSI document is being modified, it was decided to reference the working document of the ISO available at the time of this text.]

5.2 Developments in New Zealand

5.2.1 The New Zealand Building Code

New Zealand took an interest in performance-based regulations in the late 1980s and early 1990s. As a result, the 1992 version of the *New Zealand Building Code*[28] was promulgated as a performance-based document that considers Outbreak of Fire, Means of Escape, Spread of Fire and Structural Stability During Fire as specific fire safety criteria that must be addressed by any building design. The *New Zealand Building Code* is similar to the British regulations in that the wording is flexible and there are default "Acceptable Solutions" (a set of prescriptive, deemed-to-satisfy solutions to the performance requirements). However, the *New Zealand Building Code* goes somewhat further by providing more detail (i.e., three levels: objectives, functional requirements and performance requirements). In addition, a performance-based approach is required for some aspects of those occupancies with fire loads exceeding 1500 MJ/m^2.[35]

The three levels of the *New Zealand Building Code* (Objective, Functional Requirement and Performance) that must be addressed for each of the four fire safety criteria listed above can be illustrated by looking at one of the fire safety clauses: Means of Escape (words in italics are defined in the *New Zealand Building Code*):[36,63]

Clause C2 - MEANS OF ESCAPE

Objective

C2.1 The objective of this provision is to:
(a) Safeguard people from injury or illness from a *fire* while escaping to a *safe place*, and
(b) Facilitate *fire* rescue operations.

Functional Requirement

C2.2 *Buildings* shall be provided with *escape routes* which:
(a) Give people *adequate* time to reach a *safe place* without being overcome by the effects of *fire*, and
(b) Give fire service personnel *adequate* time to undertake rescue operations.

Performance

C2.3.1 The number of *open paths* available to each person escaping to an *exitway* or *final exit* shall be appropriate to:
(a) The *travel distance*,
(b) The number of occupants,
(c) The *fire hazard*, and
(d) The *fire safety systems* installed in the *firecell*.

C2.3.2 The number of *exitways* or *final exits* available to each person shall be appropriate to:
(a) The *open path travel distance*,
(b) The *building height*,
(c) The number of occupants,
(d) The *fire hazard*, and
(e) The *fire safety systems* installed in the *building*.

C2.3.3 *Escape routes* shall be:
(a) Of *adequate* size for the number of occupants,
(b) Free of obstruction in the direction of escape,
(c) Of length appropriate to the mobility of the people using them,
(d) Resistant to the spread of *fire* as required by Clause C3 "Spread of Fire,"

(e) Easy to find as required by Clause F8 "Signs,"
(f) Provided with *adequate* illumination as required by Clause F6 "Lighting for Emergency" and
(g) Easy and safe to use as required by Clause D1.3.3 "Access Routes."

5.2.2 The Fire Engineering Design Guide

As with the British code, the New Zealand code does not define "critical conditions" in terms of fire safety engineering criteria. However, guidance is available in a separate document, the *Fire Engineering Design Guide*,[35] published by the Centre for Advanced Engineering at the University of Canterbury. The *Design Guide* contains not only fire safety design criteria and methods, but also the applicable portion of the New Zealand code. In addition, the *Design Guide* covers such topics as a fire engineering design strategy, fire behaviour, pre- and post-flashover fires, fire modeling with computers, means of escape and active systems (i.e., detection, suppression and smoke control).

The fire engineering design strategy, as outlined in the *Design Guide*, is as follows:[35]

- Assume the worst or most likely location for first ignition.
- Assume the worst likely arrangement of combustible materials for the projected life of the building.
- Estimate the rate of fire development, temperature rise and smoke production.
- Estimate the activation time for detection and suppression systems.
- Throughout the development and burning phases, consider the likely movement of people, smoke and fire.
- For life safety, continue the analysis until all occupants are deemed safe with additional allowance for safety of firefighters.
- For a neighboring property and public safety, continue the analysis for the full duration of the fire to ensure that external walls do not collapse and external openings do not increase an area, thereby allowing fire spread.
- For the owner's property protection, continue the analysis for the full duration of the fire to ensure the damage is minimized.
- For hazardous substance fires, ensure that excessive toxic products are not released.
- Repeat the procedure with altered parameters.

Although the general framework outlined in the *Design Guide* is sound, it is somewhat lacking in its guidance for selecting fire scenarios (e.g., the worst location for fire ignition and the most likely location for fire ignition can be quite different: should both be evaluated?), design fires and other critical factors such as safety factors, sensitivity and reliability concerns. Future editions of the *Design Guide* are likely to address these issues in more detail. (These factors are discussed in later chapters of this text.)

A basic flow chart for this fire engineering design process is shown in Figure 8.

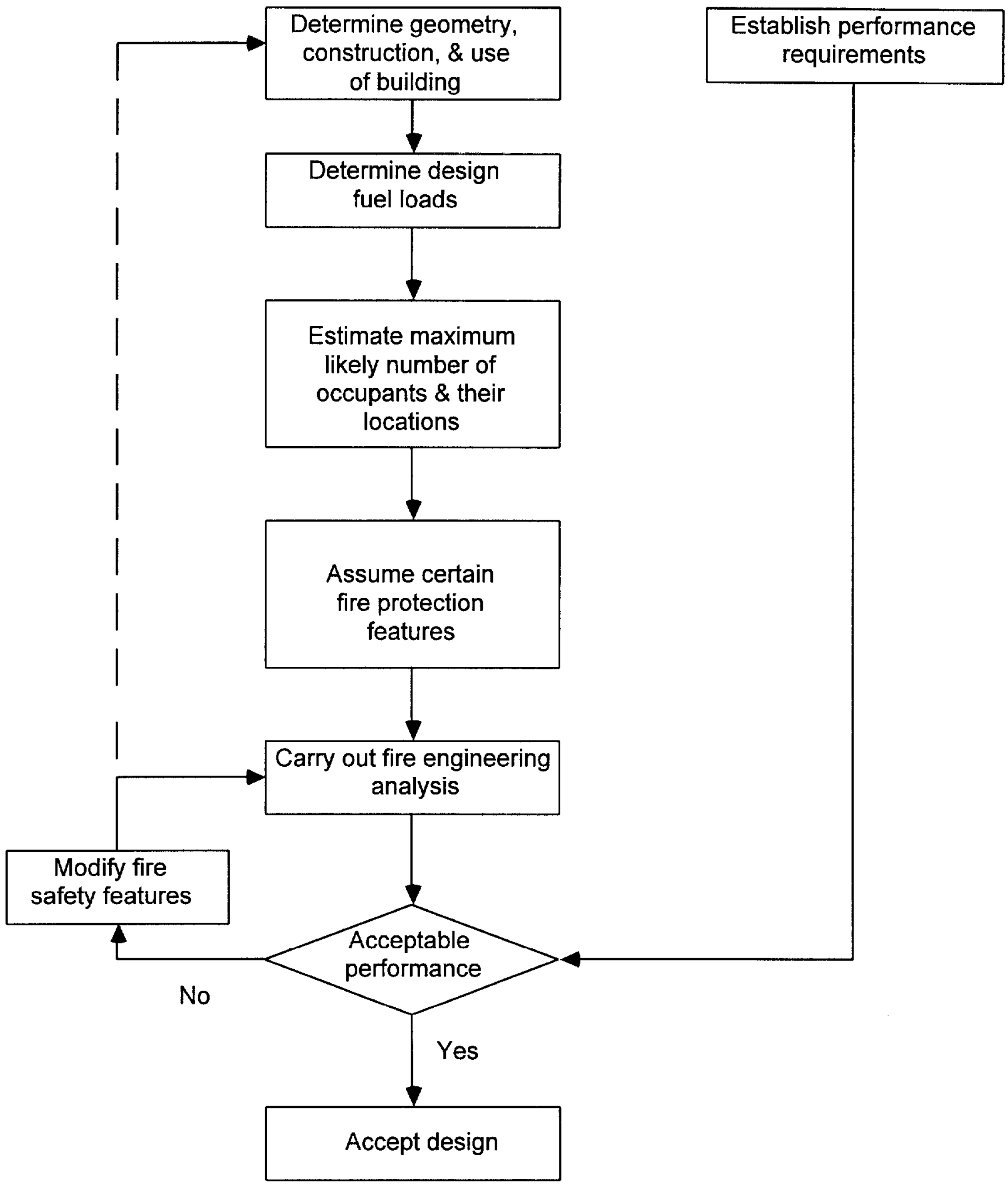

Figure 8 - Overview of Specific Fire Engineering Design[35]

5.3 Developments in Canada

5.3.1 The Canadian Building Code Situation

The building and fire codes in Canada are currently prescriptive in nature and can be broken down into three levels: The National Building Code (a model code) at the top level; the provincial regulations in the middle (regulatory documents); and municipal/city enforcement at the third level. In the mid 1990s, the Canadian Commission on Building and Fire Codes (CCBFC) became aware of concerns over the increasing complexity of the codes and their impact on costs.[39] There was also a growing awareness of the import of building and fire regulations on Canada's economic and competitive position internationally. In response to these factors, the CCBFC decided in 1994 to establish a task group to develop a long-term strategy to deal with the Canadian building and fire codes needs. The intent would be for this strategy to be used as a guide for the development of the building and fire codes into the next century.

One area of the Task Group's focus was on the international trend towards performance- or objective-based codes and standards. As the CCBFC draft strategic plan reported,[39] objective-based codes are "a set of code documents which are based on a set of explicitly stated objectives." As with the other performance-based codes, the objectives of the code are stated in terms of a hierarchy of requirements. The following is an example of how a three-tiered approach might look:

- *General Objective*: Public Health
- *Specific Objective*: Safeguard people from injury caused by structural failure
- *Specific Functional Requirement*: A building shall be provided with safeguards against fire spread so that occupants have time to escape to a place of safety without being overcome by the effects of fire.

In some cases, specific performance criteria would be set by the code in order to gauge the building's performance against the requirements.

In discussing the reasons for the transition towards an objective-based code, the CCBFC Strategic Planning Task Group cited many of the situations common to the other countries. Among others, these include the complexity of the existing prescriptive codes, the ability to provide more clarity of the intent of the code under an objective-based format, and the ability to better develop innovative solutions to fire safety design problems that were difficult to accept under the current prescriptive code format. Finally, a performance format would provide a clear indication of the performance requirements the products must meet. This would make it easier for the export of Canadian products by making it easier to demonstrate the expected level of performance to other countries.

The CCBFC Strategic Planning Task Group recommended that a transition begin with the content of the existing 1995 Code, which would be restructured to an objective-based format. The objectives, in relation to current Code articles, would be clearly outlined and published separately in a supporting document. Such an approach would facilitate the adoption of performance criteria to support a performance-based design approach, while at the same time allowing for the use of a prescriptive approach. The result would be a dual track approach wherein one would have a choice between meeting performance criteria that are consistent with the intent of the Code (i.e., undertake an engineered solution), or by simply adopting an "acceptable solution" based primarily on current prescriptive requirements.

At the end of the transition period, currently targeted for the year 2001, a fully objective-based code would be available along with a set of supporting documents. Among the supporting documents would be a set of acceptable solutions which would be "deemed to satisfy" the functional objectives of the code. New and alternative acceptable solutions could be established as technology emerges and new products evolve. As in other countries, the ultimate success of such an approach will depend highly on the availability of products and systems (from educational needs, to engineering tools, to the provision of appropriate administrative services) that support a full range of code users.

The vision for the CCBFC Strategic Planning Task Group can be best summarized using the words from the Task Group itself:[39]

> Adopting the objective based code approach is going to provide the code users with clearly stated guidance on why a specific requirement exists (the objective that it is addressing). Such a system will provide a level of guidance on interpretation which, in the past, has not been available to anything like the same extent. The adoption of a dual track system [author's note: dual track meaning objective-based or prescriptive-based alternative] will provide greater flexibility for the designer to produce innovative designs. At the same time, by simplifying the basic code structure and by providing clearly specified, 'acceptable solutions,' there will be a significant reduction in the cost and effort associated with codes related construction activity.

Following along this vision, by early 1996 the Institute for Research in Construction's Canadian Code Centre envisaged an objective-based framework consisting of the following components:[63]

- A set of objectives of ever-increasing specificity
- Mandatory requirements with specific links to objectives
- "Acceptable solutions" and "approved documents" linked to the requirements in the second component.

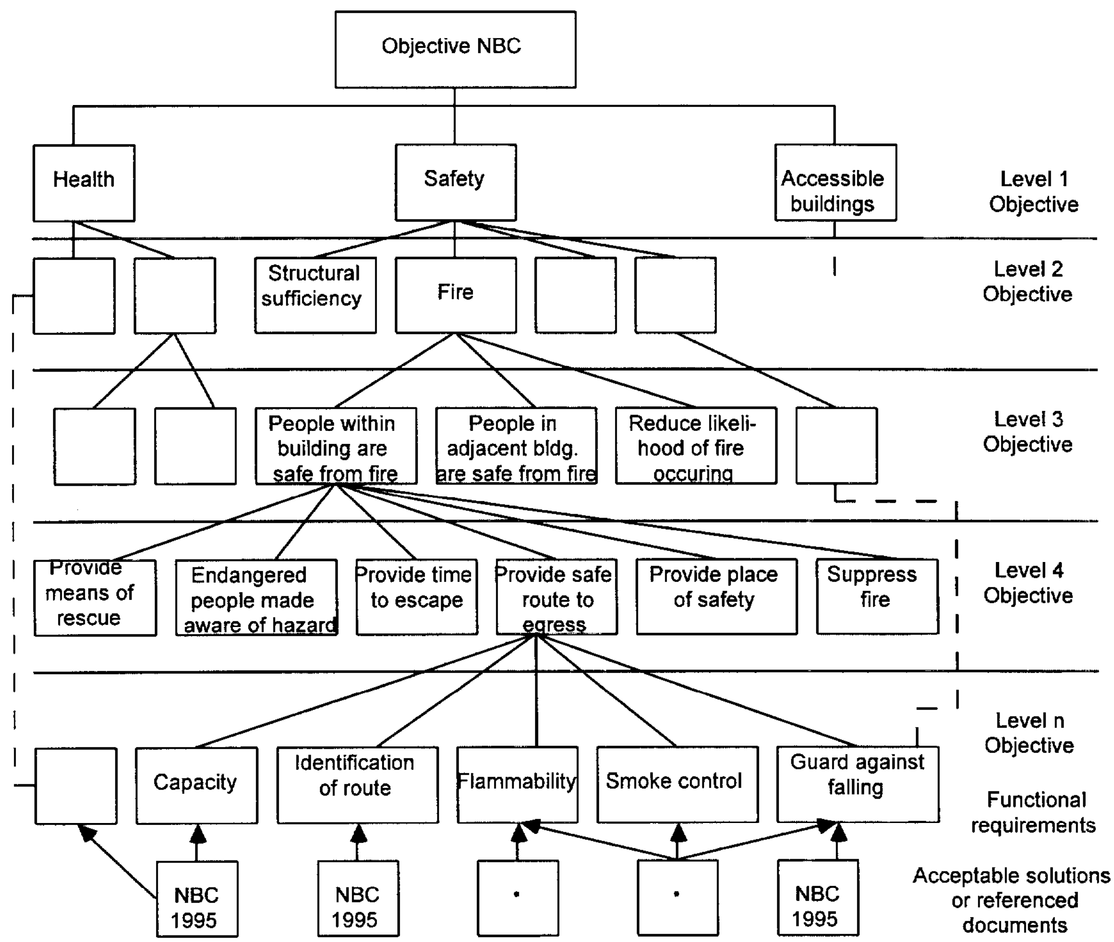

Figure 9 - Proposed Canadian Objective-Based Code Structure (from Figure 1, Reference 63).

The relationship of components in this framework is illustrated in Figure 9. The top-level objectives relate to fundamental issues, such as providing a healthy and safe environment. For each fundamental objective, a set of more detailed objectives, in the form of functional objectives, will be provided. These will likely include such objectives as safeguarding people from structural failure and safeguarding people from injury due to fire. Below these functional objectives will be a set of functional requirements. These will be statements that relate to the performance of the building and its systems in terms of structural strength, material flammability, and the like. This will provide criteria against which engineered solutions, should they be used, can be evaluated. For those who do not want or need to apply engineered solutions, a set of "acceptable solutions" will be available. These will likely be a variation of the current codes (i.e., prescriptive documents).

5.3.2 The Development of FiRECAM

Joint development of FiRECAM, a fire risk-cost assessment model by David Yung of the National Research Council Canada/National Fire Laboratory and Vaughan Beck of the Victoria University of Technology in Australia, progressed in the early 1990s in Canada.[20,21] FiRECAM was developed as a tool to assess the expected risk to life of occupants and the expected costs for protection and property losses from fires in buildings. It uses stochastic and deterministic models to predict these variables based on a wide variety of possible building fire scenarios. The probability of occurrence of each fire scenario is based on statistics. Expected loss of life and property, as a result of the occurrence of each fire scenario, are based on deterministic modeling of fire growth and propagation and occupant evacuation modeling. The expected risk to life for occupants in a given scenario is determined by the life loss expected in that scenario times the probability of the scenario occurring. The overall expected risk of life loss from fires in a building is the sum of all expected risks to life of all fire scenarios over the expected life of the building. Similarly, the total expected property loss from fires in the building is a summation of the products of property loss from each fire times its probability of occurrence.

The fundamental relationships within the model are the same as shown in Figure 6. In essence, FiRECAM evaluates the performance of fire safety design measures in terms of two parameters: Expected Risk to Life (ERL) and Fire Cost Expectation (FCE), as discussed on page 17. When running the model, the user selects fire scenarios that represent a wide range of possible fire situations for the building or building design under evaluation. These situations include smoldering fires, flaming non-flashover fires, and flashover fires, with doors open and closed, and during day and night. The probability of occurrence of each design fire is based on statistical data. The fire growth model calculates room temperature and the production and concentration of toxic gases as a function of time for a given burning rate. The model then determines the occurrence of five key events: time of fire cue, time of smoke detector activation, time of sprinkler activation, time of flashover and time of fire burnout. The detection times are used to estimate the time available for evacuation. The Fire Brigade Action Model uses flashover time to evaluate the effectiveness of manual fire fighting activities. The Smoke Hazard Model calculates the smoke hazard using not only burnout time, but also smoke movement within the building.

If the necessary data are available, the model can support performance-based design of fire safety measures for a building. It can also be used to compare the relative life risks and protection costs of alternative designs with prescriptive code compliant designs. Case studies have been described in the literature to illustrate this application.[20,21] The key factor to the overall effectiveness of the model will likely be the availability and reliability of probabilistic and statistical input data. Some believe that this model may serve as one basis for future performance-based code development in Canada[64] as well as a fundamental part of a probabilistic approach to fire safety design under the Performance Building Code of Australia (see additional discussion under Australia).

5.4 Developments in Sweden

Much like other building regulations discussed thus far, the building regulations in Sweden underwent a change in the early 1990s from prescriptive to functional. The Swedish regulations now contain performance wording throughout. This can be seen in an excerpt from the *Swedish Board of Building, Housing and Planning, Building Regulation BFS 1993:57*, Chapter 5 - Safety in Case of Fire, Section 5:3 - Escape in the Event of Fire:[34]

> **5:31 General**
>
> Buildings shall be designed so that *satisfactory escape* can be effected in the event of fire. Special attention shall be paid to the risk that persons may be injured by the fall of elements of structure or due to falls and congestion, and to the risk that persons may be trapped in recesses or dead ends.
>
> > **Note**: Satisfactory escape implies either complete evacuation of all persons who are present in a building or - as may arise in, e.g., institutional buildings or very tall buildings - escape by persons who are in the part directly affected by the fire to a place of safety inside the building. In the latter case it must be possible for protection against heat and toxic gases to be provided during an entire fire sequence or at least during the time which in the most unfavourable instance is required for a fire under the conditions in question to be completely extinguished.

Unlike the British approach that places guidance in a separate Code of Practice, not in the Regulations, the Swedish Building Regulation has design criteria embodied within. As noted above, the General Requirements from Swedish Building Regulation BFS 1993:57 state that "Buildings shall be designed so that *satisfactory escape* can be effected in the event of fire," but do not specify how this is to be achieved. However, instead of relying on a separate document to provide guidance in this area, the desired design criteria follow under subsequent headings. For example, the design criteria for designing safe escape routes with the Swedish regulations are as follows (excerpted as written): [34]

> **5:36 Design conditions**
>
> **5:361 Critical conditions in the event of escape**
>
> In design with respect to the safety of escape, the conditions in the building shall not become such that the limiting values for critical conditions are exceeded during the time of escape.
>
> > **Note**: In evaluating critical conditions, consideration should be given to visibility, thermal radiation, temperature, noxious gases and the combination of temperature and noxious gases. The following limiting values can normally be applied:
> >
> > Visibility: level of fire gases not lower than 1.6+(0.1xH) m, where H is the height of the room,
> >
> > Thermal: a short term radiation intensity of maximum 10 kW/m^2,

Radiation: a maximum radiant energy of 60 kJ/m^2 in addition to the energy from a radiation of 1 kW/m^2,

Temperature: air temperature not higher than 80 °C.

In this case, there is both a functional requirement, (i.e., not to exceed "limiting values for critical conditions") as well as guidance that gives specific values for these limits. Unlike more prescriptive codes that may require a certain flame spread rating or smoke production limitation, this regulation does not set prescribed limits for building materials, rate of flame spread, smoke production and the like. Instead, it states defined fire safety engineering design criteria to assist the engineer in evaluating various physical factors that can influence safe evacuation. By stating these limiting conditions in terms of depth of smoke layer, radiation thresholds and temperature thresholds, the engineer can evaluate a variety of scenarios, building materials and so forth using the many available empirical relationships and computer fire modeling techniques. In essence, the Swedish approach is a combination prescriptive-performance regulation.

This differs from the British approach that has functional requirements in the regulations, and guidance for the design and evaluation process in a separate code of practice. However, in the end, both the Swedish and the British approaches provide for flexibility in design while setting boundary conditions that should not be exceeded for fire and life safety.

5.5 Developments in Australia

5.5.1 The Fire Code Reform Centre and the Building Code of Australia

The Australian Building Codes Board (ABCB), prompted by the developments towards the National Building Fire Safety Code, the *Warren Centre Report* and the ongoing work of Beck at the Victoria University of Technology (VUT), formed the Fire Code Reform Centre Ltd. (FCRC) together with government and private organizations in 1994.[13,38,65] The FCRC is a national, industry-wide, non-profit corporation that is facilitating a major reform of the *Building Code of Australia* (BCA). The mission of this organization is to promote the Warren Centre Project recommendation that a national strategy be developed for research, development, application and education relevant to fire safety engineering design.

The primary task of the FCRC is to facilitate the development of a new *Building Code of Australia* in the format proposed by the Building Regulations Review Task Force.[24] The new code is not intended to replace the current prescriptive requirements, but rather to provide an alternative means of regulatory compliance. At the time this text was being prepared, a draft version of the Performance BCA has been released for public review and comment.[39]

As presented, the draft Performance BCA is structured in a four-tiered, hierarchical format consisting of Objectives, Functional Statements, Performance Requirements and Deemed-to-Satisfy or Alternative solutions (see Figure 10).

The objectives interpret what the community expects from the BCA provision to which they apply (societal goals). Objectives are primarily expressed in general terms and usually refer to the need to safeguard people, provide an acceptable level of amenity and protect adjoining buildings. For example, an egress objective is to "safeguard people from illness or injury when evacuating a building to a safe place during a fire or other emergency."

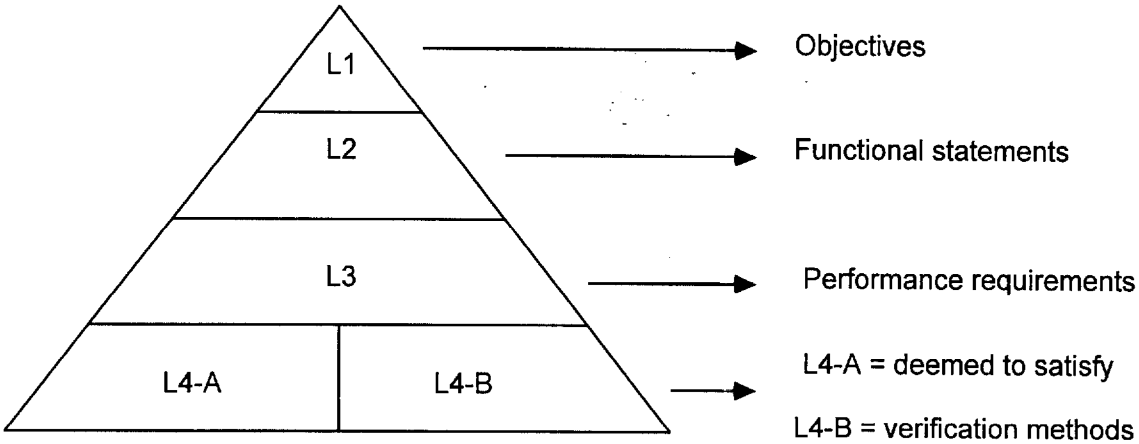

Figure 10 - Building Code of Australia Hierarchy[38]

The functional statements set out, in general terms, how a building could be expected to satisfy the objectives. For example, "a building is to be provided with means of evacuation which allow people time to evacuate to a safe place without being overcome by the effects of fire or other emergency."

The performance requirements go a level deeper and outline a suitable level of performance (by the building materials, components, design factors, and construction methods) for a building to meet the relevant functional statements, and in turn, the relevant objectives. For example, "general access routes, exits, paths of travel to exits and continuous accessible paths of travel must have slip resistant walking surfaces on ramps and stairway treads, have stair treads which prevent people falling through treads where open risers are used," etc.

To satisfy the upper tiers, there are both deemed-to-satisfy provisions and the option to use alternate methods. The deemed-to-satisfy provisions include examples of materials, components, design factors and construction methods which, if used, will result in compliance with the performance requirements of the BCA. However, there is no obligation to adopt any particular material, component, design factor, or construction method (such as provided in the deemed-to-satisfy provisions) as long as it can be demonstrated that the proposed alternative complies with the relevant performance requirement. The key to demonstrating compliance will be through the use of acceptable, or listed verification methods, some of which will be made part of the performance BCA in the future.

5.5.2 The Fire Engineering Guidelines of Australia

Concurrent with the 1994 project to adapt the Building Code of Australia (BCA) to a performance-based document, the Fire Code Reform Center Limited (FCRC) developed a guidance document on engineered fire safety design. This document, *Fire Engineering Guidelines*,[41] provides a framework for an engineering approach to fire and life safety in buildings. It gives guidance on the application of scientific and engineering principles to the protection of people and property from unwanted fire, and provides a structured approach to assessing the effectiveness of the total fire safety system in achieving design objectives.

The *Guidelines* were developed to help designers undertake performance-based designs to meet the fire safety objectives of the Performance BCA, both as an aid to the deemed-to-satisfy provisions and as guidance for developing acceptable alternative designs. In addition, the

Guidelines acknowledge that designers may have to meet goals outside of the Performance BCA as well, such as property protection and continuity of operations.

The *Guidelines* are not intended to include all engineering design technology required for any particular design job. Rather, they provide a framework for a fire safety design process that is complimentary to the Performance BCA. Detailed quantification methods and data that can be found elsewhere are referenced. Several chapters of the *Guidelines* are used to provide an overview of the framework, discuss fire and building parameters to consider in a design, and overview evaluation methods to assess proposed designs. The fundamental components of the framework include:

- Conceptual design
- Fire Engineering Design Brief (FEDB)
- Quantified analysis
- Fire scenario analysis
- Evaluation of design alternatives
- Selection of design
- Reporting and documentation

The FEDB describes the process for determining fire safety objectives and acceptance criteria, and for gaining agreement on these from the approving authorities. The design brief also involves trial designs, quantitative analyses and evaluation of design alternatives against the acceptance criteria. The overall process is illustrated in Figure 11 Figure 12 illustrates the quantitative analysis.

The quantitative analyses can become quite involved. For this reason, the analyses are divided into six fundamental groupings, or sub-systems (SS), as illustrated in Figure 13.

A significant difference between the Australian approach and those of the United Kingdom and the International Organization for Standardization (to be discussed in Section 5.6) is the identification of three levels of evaluation in the Australian *Guidelines*:[41]

- Level 1: Component and Sub-system Equivalence Evaluation
- Level 2: System Performance Evaluation
- Level 3: System Risk Evaluation

A Level 1 analysis is used when trying to establish equivalency of a component or system to a requirement specified by regulation, such as in the Performance BCA. Using an engineered approach to determine the spacing of heat detectors instead of applying the spacing-rating requirement as stated in the regulations, is one example.

A Level 2 analysis would be used to evaluate the whole, or substantial part, of the fire safety system. This level of analysis accounts for the interaction of two or more sub-systems and is much more complex than that of a Level 1 analysis. A large variety of fire scenarios and design alternatives will likely be involved. An example of a Level 2 analysis is the design of a smoke management system to the life safety provisions of the Performance BCA. Here, the designer considers such factors as fire growth and propagation, smoke development and spread, detection and suppression system activation times, occupant alerting and evacuation.

A Level 3 analysis would be used for highly complex or innovative buildings where a more comprehensive and sophisticated analysis could lead to cost-effective solutions to a difficult problem. Based on a probabilistic risk assessment (PRA) approach, Level 3 analysis may result in solutions that are significantly different from the regulations. This level of analysis requires the highest level of skill of the fire safety engineer and the approval authority. In addition to the deterministic analyses required in a Level 2 analysis, the probabilistic risk assessment of the Level 3 analysis requires one to assign probabilities and frequencies of event occurrence (these might include system activation or failure, fire occurrence, response of people to a given signal or at a given time, etc.). The three levels are illustrated graphically in Figure 14.

Overall, the *Guidelines* provide a comprehensive framework for a performance-based analysis or design of building fire safety. Although written for fire engineers, it can be used by building and fire officials reviewing performance-based designs.

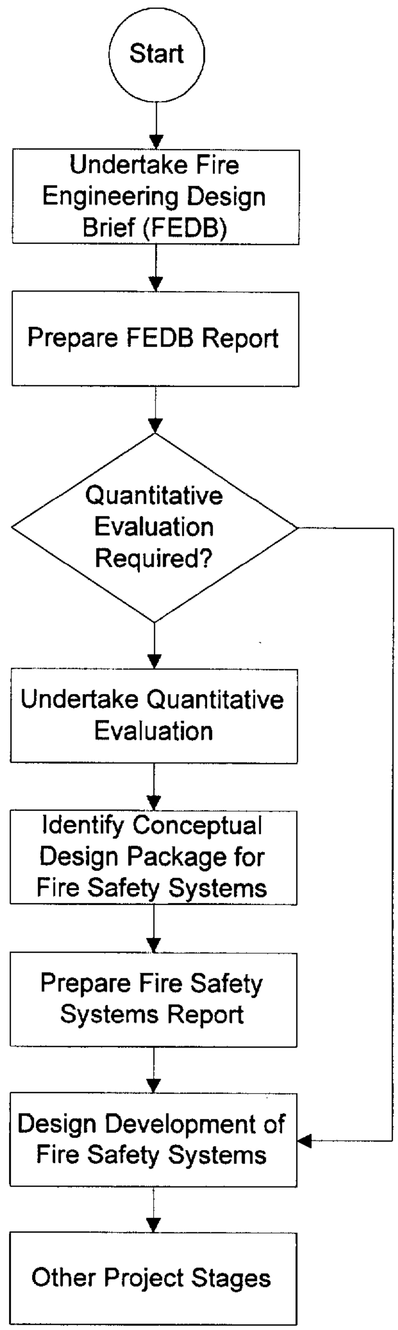

Figure 11 - Conceptual Design Procedure for Fire Safety Design (from Figure 3.2, Reference 41)

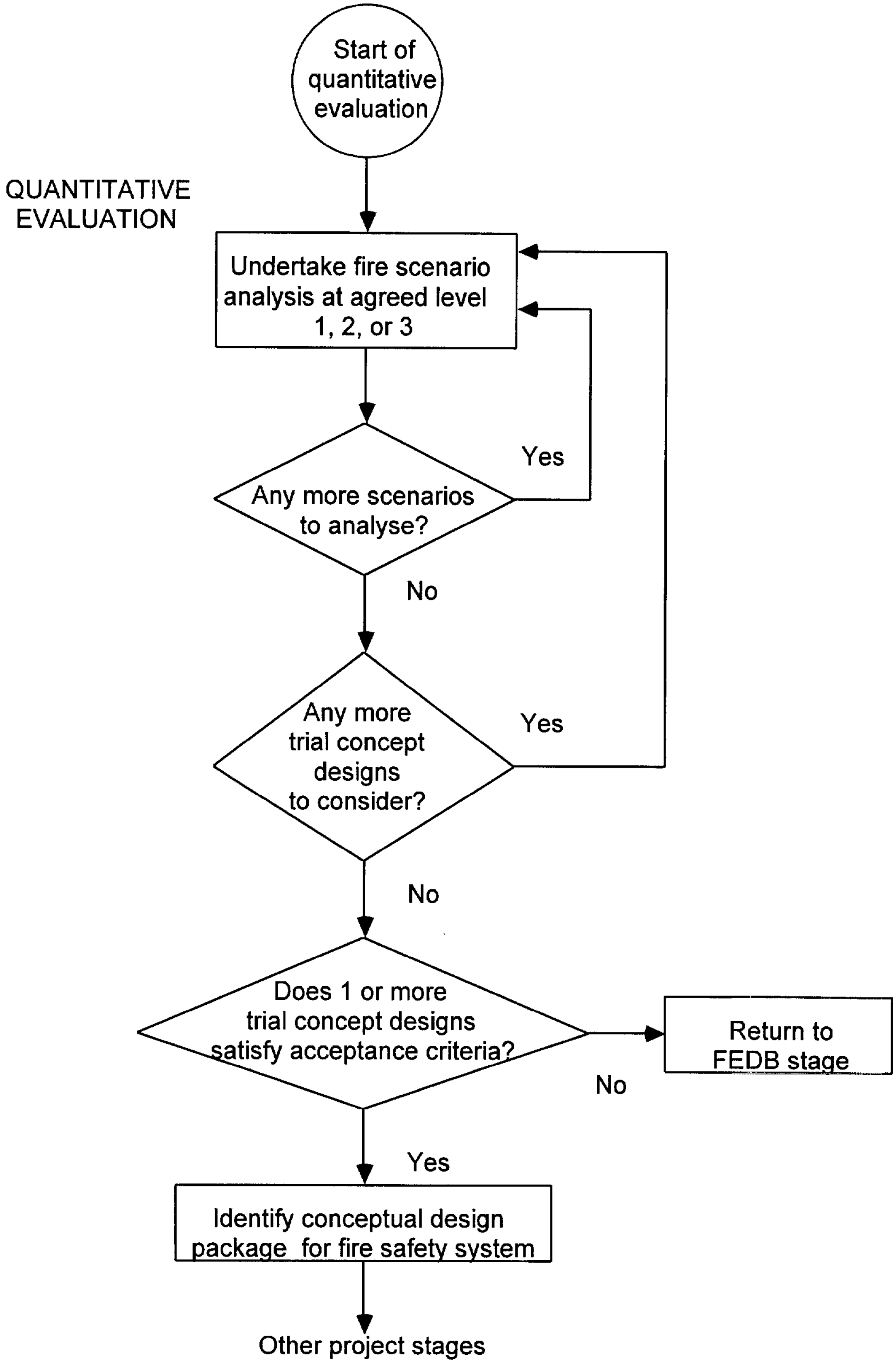

Figure 12 - Procedure for Quantitative Analysis (from Figure 3.3, Reference 41)

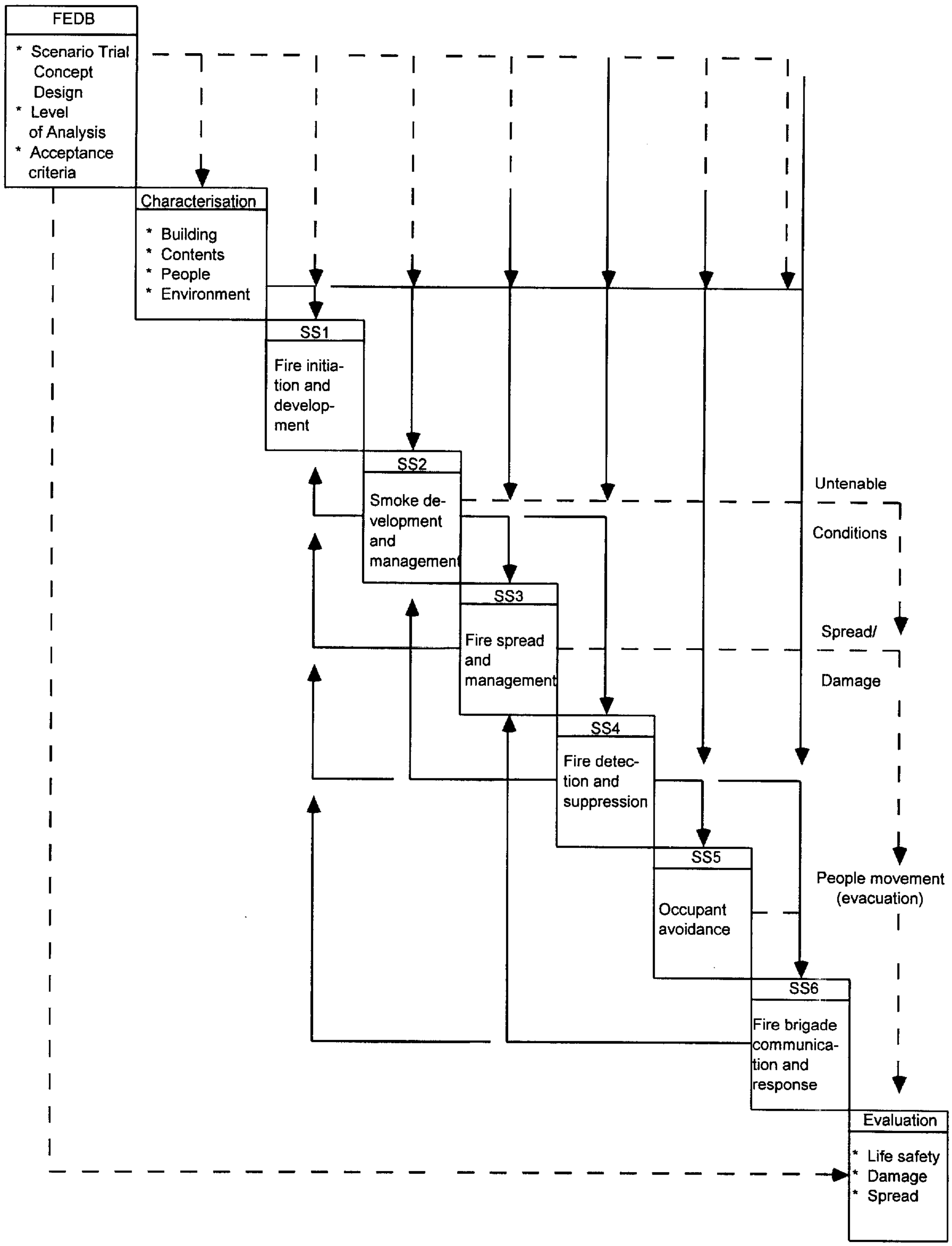

Figure 13 - Fire Scenario Analysis Showing Typical Interaction between Sub-systems (from Figure 3.5, Reference 41)

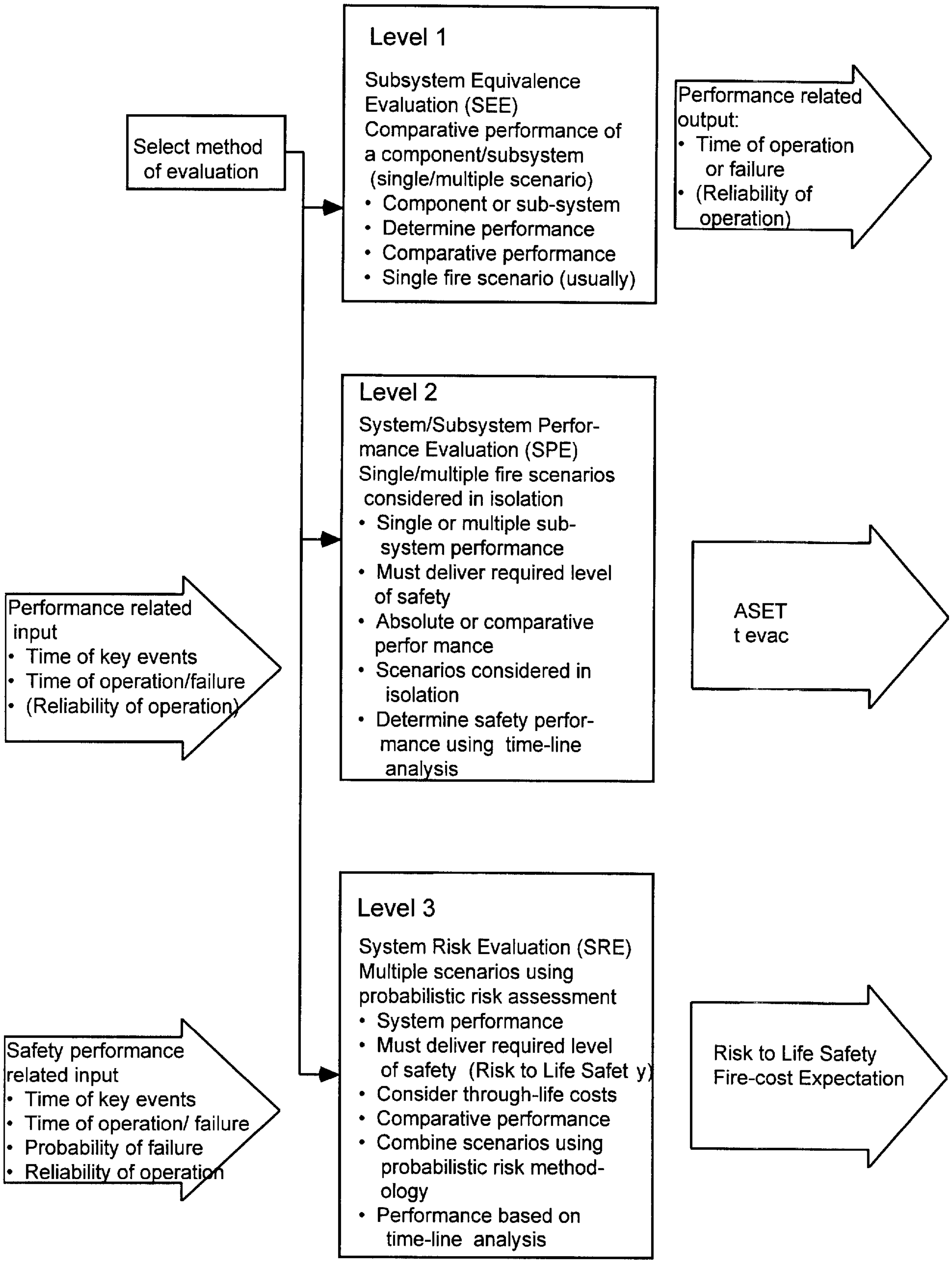

Figure 14 - Methods of Evaluation Flow Chart (from Figure 6.2, Reference 41)

5.6 The Role of the International Organization for Standardization (ISO) and the International Council on Building Research and Documentation (CIB)

5.6.1 The International Organization for Standardization (ISO)

The International Organization for Standardization (ISO) also became a prominent player in the area of performance-based fire safety design in the early 1990s. In 1990, the members of ISO Technical Committee (TC) 92, whose primary responsibility is for fire tests on building components and structures, recognized the need for the evaluation and standardization of the engineering methods used for fire safety design on an international basis. To address this issue, ISO TC92 formed a sub-committee on Fire Safety Engineering (SC4).[25]

The members of SC4 chose to focus their initial work on fire safety in buildings, and formed five Working Groups (WG) to address this topic:

WG1 - Application of Fire Safety Performance Concepts to Design Objectives
WG2 - Initiation and Development of Fires and Movement of their Effluent
WG3 - Fire Spread Beyond the Compartment of Origin
WG4 - Detection, Activation and Suppression
WG5 - Evacuation and Rescue.

WG1 coordinates the work of the other WGs so that the various components fit together in the overall design approach. In developing the design approach, WG1 considered the following parameters as important components for any design process:[25,66]

- The definition of fire safety objectives and establishment of appropriate acceptance criteria.
- The establishment of prescribed design parameters, incorporating a review of the architectural design in reviewing the possible alternative fire safety strategies.
- The characterization of the building and its occupants (i.e., estimating and including design parameters not provided by the architect).
- The undertaking of a fire hazard analysis, incorporating the identification of potential fire hazards and their possible consequences in selecting those fire scenarios that form part of the quantified analysis.
- The undertaking of a quantified (engineering) analysis.
- An assessment of the outcome of the analysis against the fire safety criteria.
- Adequate presentation and documentation of the analysis and design.

The basic process considered within the WG1 framework is illustrated in Figure 15. Due to the large number of factors involved in such an analysis, WG1 had suggested a Global Information Bus to represent the interactions of various sub-systems. Within this system, there are five sub-systems:

- Sub-System 1 - Initiation and development of fire and fire effluents.
- Sub-System 2 - Movement of fire effluents.
- Sub-System 3 - Fire spread beyond a compartment.
- Sub-System 4 - Detection, activation and suppression.
- Sub-System 5 - Evacuation and rescue.

> The Global Information Bus is analogous to a computer data information bus wherein a number of input and output devices connect to a common information bus (multi-channel data transfer mechanism), and proper information is put on the bus and taken off the bus as necessary.

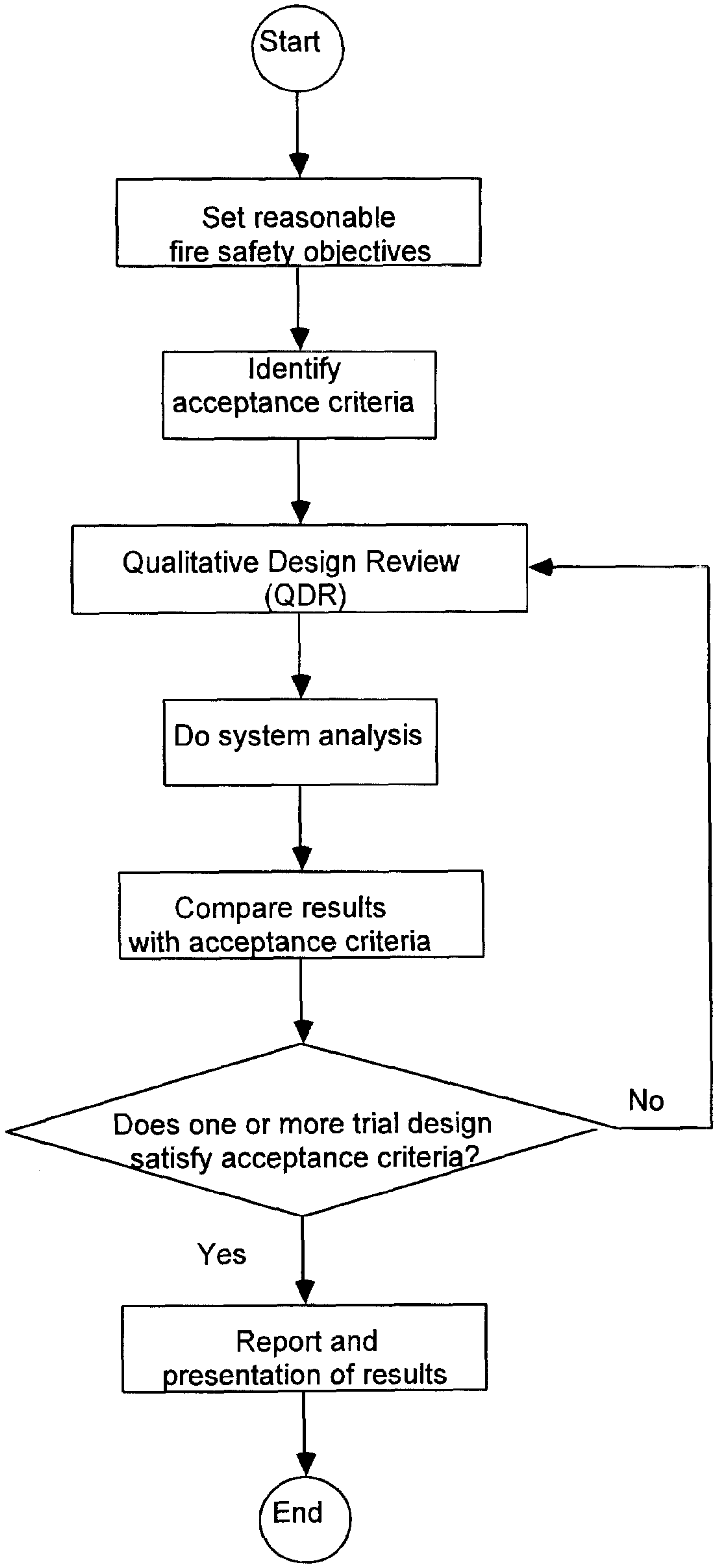

Figure 15 - Basic Design and Analysis Procedure (from Figure 2, Reference 65)

The Global Information Bus, illustrated in Figure 16,[66] is made up of a number of channels, each carrying one or more pieces of data which may vary with time following ignition. Values for the candidate design are then input on to the Global Information Bus. Engineering analysis then performed converts the input of the candidate design to output, which is again placed on the appropriate channel of the Bus. For the most part, these engineering analyses reside in each of these five Sub-Systems of the framework. In this manner, data developed in Sub-System 2 can be used where necessary by the other Sub-Systems. An additional step is required where a probabilistic risk assessment is added to the process.

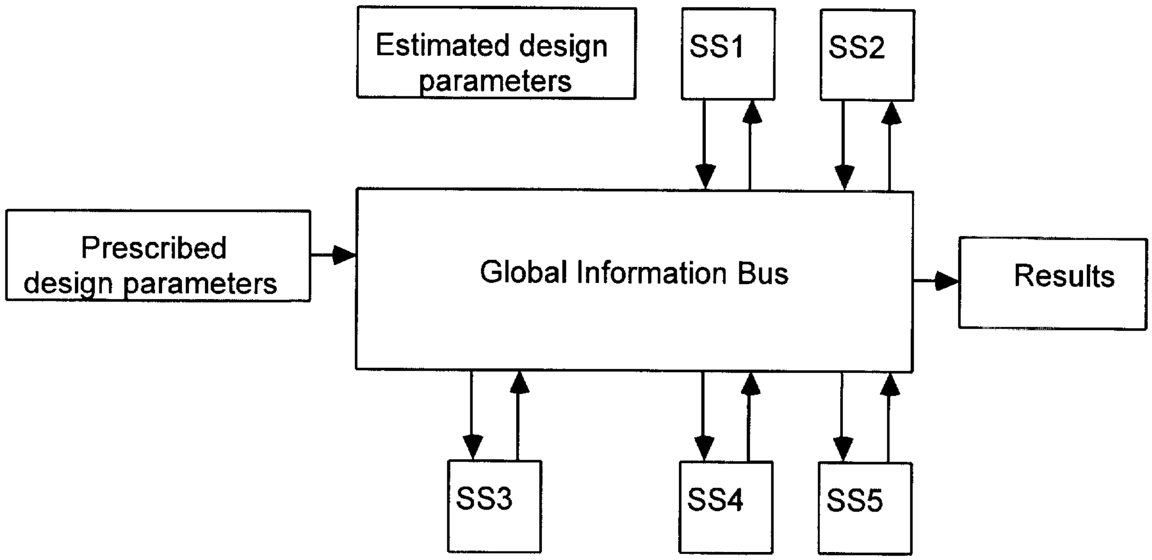

Figure 16 - Relationship of Design Parameters and Sub-Systems to the Global Information Bus (from Figure 6.6.1, Reference 65)

Much like the Building Fire Safety Evaluation Method (BFSEM) discussed in Section 3, the ISO approach is being developed as a highly detailed and rigorous procedure which can assist a designer and a design reviewer through the detailed process of building fire safety analysis and design. A public version is expected to become available in 1997.

5.6.2 The International Council on Building Research and Documentation (CIB)

The International Council on Building Research and Documentation (CIB) became active in the support of performance-based fire safety design methods in the 1990s as well. The CIB is an international organization dedicated to the advancement of building technology through research studies and dissemination of information. Its membership includes private and national test laboratories and construction research organizations, academia, and concerned individuals. Similar in concept to the ISO, CIB has a number of Working Commissions (W) and Task Groups (TG) that focus on specific issues, from construction to society to the environment.

CIB Working Commission 14 (W14), Fire, has the charge of coordinating fire-related issues for buildings and construction. The issues run the range from fire test criteria through occupant evacuation considerations. In 1994, CIB W14 established two sub-groups to look more closely at the issue of performance-based design for building fire safety: Engineering Evaluation of Building Firesafety and Validation of Fire Models.[33]

It should not be surprising that these topics are closely related to ISO activities. This is due, in part, to a formal liaison between CIB and ISO. In addition, many of the CIB W14 members are representatives to ISO as well. In some respects, the relationship between CIB and ISO can be viewed as pre-standardization and standardization, where CIB member organizations provide much of the research data to support ISO standards. This relationship also works in reverse, when CIB members transfer work performed at the ISO level into practice through their organizations.

On the building code side, CIB formed Task Group 11 in 1994 to study performance-based building codes. The objective of the group's work is to provide information to assist those countries developing regulatory systems. To accomplish this, a variety of specific tasks were identified:[32]

- Develop framework(s) for performance-based regulatory systems.
- Identify useful sources of knowledge and tools.
- Identify priority areas where knowledge is not sufficient.
- Document approaches and experiences.
- Make recommendations to CIB.
- Define "performance-based building code."

To study individual parts of a complete performance-based regulatory framework, a number of sub-groups were established within TG11. Topics for study included:

- User's needs, including those whose needs are primarily directed towards the development or construction of buildings, and those whose needs are primarily directed toward occupancy of a finished building;
- Terminology used in performance codes;
- A framework for performance codes;
- Language structures used in expressing performance requirements;
- Software tools to support development in use of performance codes;
- Educational requirements for performance codes; and,
- A summary of experiences and solutions adopted in implementing a performance-based approach to regulations and codes.

In reviewing the needs of those people who must work with performance-based codes, the TG 11 members developed a list of 19 items that users of performance-based codes need or want the codes to provide, including to satisfy public expectations, to be easily understood, to provide certainty in outcome, to be flexible in application, to encourage innovation, to make use of all available resources, to apply a consistent approach to risk and to provide certainty of compliance. TG11 also identified a number of areas in which additional educational efforts are required. Architects, fire safety engineers, and code writers were identified as audiences with the highest need for education. In addition, education needs are high for elected and appointed public officials, as well as the insurance industry.

The basic rationale for further education lies in the fact that the regulatory and design communities are currently accustomed to prescriptive approaches which are fairly empirical in nature; the transition to a performance-based environment requires considerably more knowledge, judgment, and sophistication in the selection and use of engineering tools. Therefore, performance-based design concepts need to be taught at the university and technical school level, especially for engineers and architects. Continuing education programs for practicing professionals can be offered by universities, technical schools, professional societies and various trade organizations. A TG11 report on Performance-Based Codes is expected in 1997.

5.7 Developments in the Nordic Countries

The countries of Denmark, Finland, Iceland, Norway, and Sweden have a long history of working together on a variety of issues, with many of the recent efforts being coordinated through the Nordic Council of Ministers. One area of cooperation is that of building regulations, for which the Nordic Committee on Building Regulations, NKB (an institution within the Nordic Council of Ministers) has responsibility. The primary function of the NKB is to coordinate the efforts of the building authorities of the member countries.[40]

In 1994, the Fire Safety Committee of the NKB was tasked with developing and implementing "fire safety regulations of the next generation" based on previous efforts within the NKB, the ECE Report on Fire Modelling, the EU Interpretative Document on Fire Safety, and the ongoing work of ISO TC92 SC4.[40] The Committee focused its efforts in two primary areas: (1) establishing safety levels, expressed as performance requirements, that would provide the opportunity to design buildings of alternate constructions which would comply with the stipulated safety level, and (2) providing guidance for undertaking designs to meet the required level of safety (performance). The result of their efforts is the two-part document Performance Requirements for Fire Safety and Technical Guide for Verification by Calculation.[40]

Part 1 of the NKB document is Fire Safety Regulations: Performance Requirements. In essence, it is a model code for the Nordic countries which lays out considerations for the fire safety performance of buildings. The regulations are provided in five sections: Stability of Load-Bearing Structures, Development and Spread of Fire and Smoke in the Building, Spread of Fire Between Buildings, The Escape of Persons, and The Safety of Rescue Personnel. It is a short document (5 pages), that, like the other performance-based codes, provides brief, non-quantified statements of the level of performance expected. For example:

> 2.3.3 A fire compartment shall be designed in such a way that it prevents the spread of fire and smoke to other parts of the compartment group during the time which is necessary for escape and for the rescue by the rescue personnel of persons in the compartment group.[40]

Unique features of the NKB Regulations are the concepts of service categories and safety classes. Service categories reflect the use of the building in terms of occupant presence and activity. There are six service categories that are defined by combinations of yes or no responses to the following four criteria:[40]

- Persons present sporadically
- Familiarity with the escape routes and exits of the building,and persons can reach safety on their own
- Only intended for awake persons
- Little activity which presents a fire hazard.

In addition, the NKB Regulations indicate that buildings and structures are to be assigned safety classes in view of the risk which a fire may pose to the safety of persons, the environment, or social consequences. The four safety classes identified are low, medium, high, and extra high. No discussion is provided in Part 1 as to what the acceptable levels of risk are or should be;

however, safety classes and service categories are discussed in more detail in Part 2, the Technical Guide.

Part 2 of the NKB document is the Technical Guide for Verification by Calculation of Performance Requirements for Fire Safety. The development of this guide was a result of the NKB Fire Safety Committee's assessment that international standardization had not yet progressed sufficiently to provide the necessary tools to assist those engaged in building fire safety design and construction.

The NKB Technical Guide covers much the same topics as the other guides discussed in this text, with sections entitled: Safety, Design Fire Process, Development of Fire in the Primary Fire Compartment, Spread of Fire and Smoke to Adjoining Fire Compartments, Spread of Fire to Neighboring Buildings, Detection, and Escape Times. Two areas in which the NKB Technical Guide differs from most other fire engineering design guides is its length (less than 40 pages) and its more detailed treatment of safety factors, safety classes, and service categories.

The concept of service categories is straightforward, and is similar to the concept of occupancy classifications in other building regulations. The difference, however, is in the use of the four criteria that describe whether people are present, know the building and can be expected to escape on their own, can be expected to be sleeping, and whether or not the normal use of the building presents higher than expected fire hazards.

These criteria tie directly to the concept of safety classes. In essence, the safety class is a means to qualify the level of risk to life, the environment, and society for each service category. The result is the range of safety classes from low, that might be given to certain small, unoccupied warehouses, to extra high, that might be assigned to a petroleum processing facility. Part of the decision-making process for assigning buildings to safety classes is based on the assignment of partial safety factors to four key parameters: fire load density, heat output of the fire, detection time, and total escape time. The limiting values used in the analysis are the ignition of materials and the safety of persons.

In the current edition of the NKB Technical Guide, the partial safety factors are all 1.0 due to the lack of data. However, the concept of using partial safety factors in building fire safety design is promising, and there is a need for quantifiable safety factors of some sort in performance-based codes and fire safety design methods. Much of the effort thus far has come from Magnusson at Lund University in Sweden,[67] and it is hoped that this effort and others will provide useful and useable data and techniques for determining safety factors in the near future.

5.8 Developments in The United States

5.8.1 Key Conference at Worcester Polytechnic Institute

In 1991, the Conference on Firesafety Design in the 21st Century,[26] was held at the Worcester Polytechnic Institute in Worcester, Massachusetts. This conference played a role in the motivation of performance-based firesafety design methods and codes in the United States similar to the Warren Centre Project in Australia just two years earlier. The two-and-a-half day conference brought together 112 participants who provided perspectives of practicing engineers, architects, the fire service, building officials, attorneys, researchers and academicians. In addition to the presentation of some 29 conference papers, the participants broke down into working groups for more detailed discussion of important issues.

The conference participants identified a number of important goals, barriers and strategies for firesafety design in the 21st century.[26] A United States national goal was formulated that "by the year 2000, the first generation of an entirely new concept in performance-based building codes be made available to engineers, architects and authorities having jurisdiction... in a credible and useful form." Perceived barriers included a lack of explicit, defined firesafety goals in building codes and standards; resistance to change and the momentum of tradition, lack of appropriate educational qualifications among key participants in the firesafety design and regulatory process; ineffective transfer of new engineering methods to practitioners in validated and useful form; economic incentives and disincentives; fear of liability and lawsuits; and failure of institutions to embrace innovation.

Several other key conferences, symposia and workshops in the 1990s have contributed significantly to the development of performance-based codes and fire safety design methods. One such symposium and workshop that warrants special note is the International Symposium and Workshops, Engineering Fire Safety in the Process of Design: Demonstrating Equivalency, organized jointly by CIB W14, the United Kingdom's Fire Research Station, and the University of Ulster, Fire SERT Centre in Jordanstown, Northern Ireland.[68] The proceedings contain a number of relevant papers as well as a transcription of questions and discussion generated by conference participants.

Strategies that were proposed to overcome the barriers and achieve the national goal included the organization of "centers of excellence" collaboratives between universities, industry and government to champion new code concepts; the development and introduction of new code concepts; the development of innovative engineering tools and methodologies and their provision in useable format; the provision of a third-party mechanism for validating innovative engineering tools and methodologies; and the strengthening of education programs for all involved concerns in the fire and building communities.

5.8.2 The Application of Basic Concepts

Soon after the Conference on Firesafety Design in the 21st Century, Richard L.P. Custer (an adjunct professor at Worcester Polytechnic Institute and president of Custer Powell, Inc.) and Brian J. Meacham (then of FP&C Consultants, Inc.) began developing the first of two courses[27, 37] on performance-based design for the Society of Fire Protection Engineers. Both practitioners of performance-based analysis and design, their intent was to translate evolving concepts into a step-by-step process for others to use. They also began writing a series of papers[69,70,71,72,73,74,75] on the subject, including "Performance-Based Fire Safety Engineering: An Introduction of Basic Concepts,"[76] based largely on material developed for the SFPE courses.

That paper described a conceptual performance-based fire protection design process developed to help the fire protection engineer identify performance objectives and quantify them as "loads" in engineering terms that are suitable for evaluation of candidate designs using available fire dynamics tools. As discussed in Reference 76, there are eight basic steps in the process: develop background information, develop performance criteria, develop fire scenarios, define design fires, develop design alternatives, develop Q_{do} and Q_{cr} for each design alternative, select final design, and prepare documentation..

Develop background information: This step includes the development of site or project information (general information relative to the building, hazards, process, or occupants), and defining client goals and loss objectives. The "client" may range from the architect or building owner to the insurance carrier or the building or fire officials. The objectives stated by clients are generally not in fire engineering terms.

Client loss objectives specify how much safety the client wants or needs (and is ultimately willing to fund). "No loss of life outside room of origin" is a sample client loss objective or statement of the client's maximum acceptable loss. Risk assessment plays an important role in this step of the process.

Develop performance criteria: Quantification of performance involves determination of the type and degree of fire stresses that equate to the stated loss objectives or acceptable losses. The criteria may be expressed as a radiant flux, a rate of heat release, a toxic or corrosive species concentration, or ceiling jet velocity.

Consider the example above of "no loss of life outside the room of origin." An acceptable design would be expected to control the fire or the distribution of its products such that the agreed levels would not be exceeded. An example of this concept is shown in Table 2.

Table 2 - Example Engineering Design Objectives in Egress Path for Life Safety

Parameter	Baseline	With Safety Factor*
Hot layer temperature	65 °C	50 °C
CO concentration for 30 min	<1,400 ppm	<700 ppm
Distance of smoke layer above floor	1.5 m	1.8 m
Visibility	2 m	4 m

*Arbitrary examples

Develop fire scenarios: A fire scenario[77] is a description of a specific fire from ignition to the maximum extent of growth and resulting damage. Scenario development considers the pre-fire situation, ignition sources, initial fuels, proximity of secondary fuels, fire growth extension potential beyond compartment, targeted loss locations, occupant conditions, other factors (such as ventilation, environmental and operational factors, time of day, etc.), and relevant fire statistics.

Define design fires: The basic fire dynamics tools used for performance-based design are based on a constant heat release rate for steady fires or on a heat release rate history for growing fires.

The analysis should result in a number of design fire curves based on the fire scenarios identified. The data can be obtained from the literature,[78] from intermediate-scale tests of free burning items using large calorimeters, or from full-scale tests. The resultant design fire curves are used to evaluate design alternatives against the established performance criteria.

Figure 17 illustrates a design fire curve. Figure 18 depicts a flow chart summarizing the design fire development process. Note that if the scenarios do not exceed the performance criteria (i.e., the fires would not produce the damage equivalent to the loss objective), the client objectives may have been too high, and different criteria can be considered.

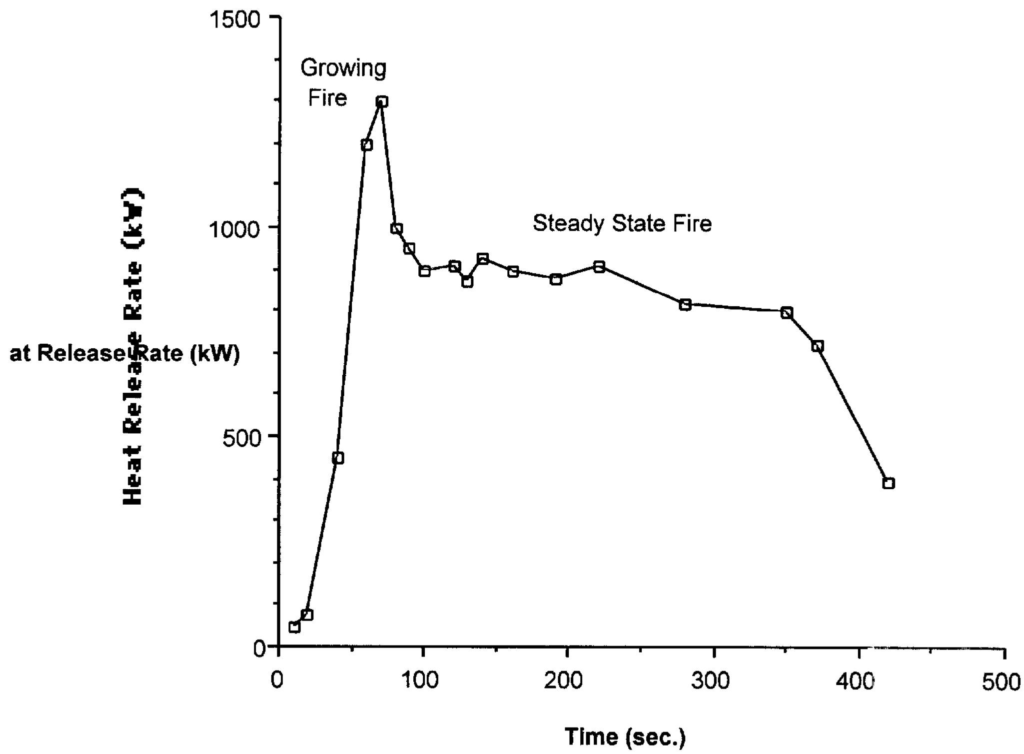

Figure 17 - Sample Design Fire Curve[74]

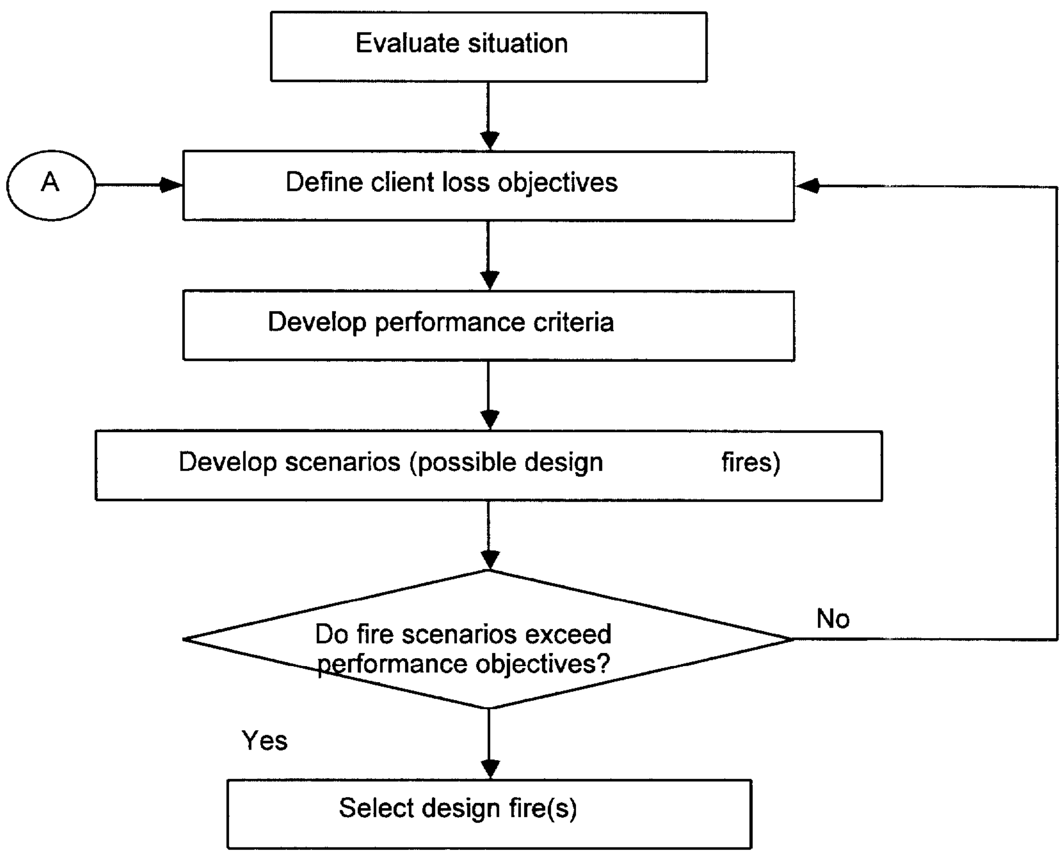

Figure 18 - Development of Design Fires[74,76]

Develop basic design alternatives: This activity results in a set of preliminary design options that are tested against the design fires. Sample alternatives include existing fire protection (if present); prescriptive code option; ignition or fuel control; rapid detection, notification, and egress; suppression; compartmentation; smoke management; or an appropriate combination of the above e alternatives.

Develop Q_{do} and Q_{cr} for different design alternatives: For a given fire safety design alternative or trial design, there will be a point (Q_{do}) on the selected design fire curve where the energy and product release rates will produce conditions representative of the design objective. Given that there will be delays in detecting the fire and responding to it), the fire will need to be detected at some time in advance of do. In order to account for these delays, a critical fire size Q_{cr} can be defined as the point on a given design fire curve at which the fire must be detected in order to meet the design objectives for a given design alternative. Figure 19 shows this relationship. The location of Q_{cr} on a design fire curve can also reflect the safety factor.

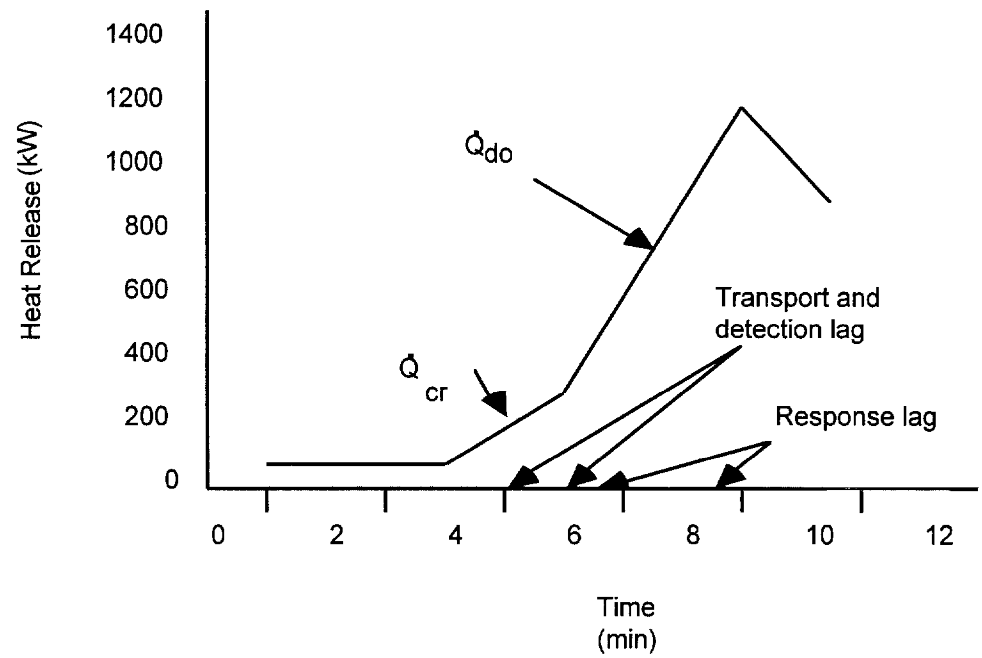

Figure 19 - Design Objective and Critical Heat Release[73,76]

Select final design(s): Selecting the final designs is an iterative process in which trial designs are tested against the performance criteria, such that the client's loss objectives are not exceeded. If they are, the design is modified or a new trial design is selected, and another evaluation is conducted. If no reasonable or cost effective design is found, the client loss objectives may be unrealistic and should be revisited and perhaps redefined at a higher level or steps made to reduce the exposure, perhaps by relocation or separation of fuels or critical functions. Figure 20 is a flow chart that summarizes the evaluation process for trial designs.

The evaluation tools range from simple hand calculations to the application of complex fire models. Many calculation methods and sample problems appear in the *SFPE Handbook of Fire Protection Engineering* and in fire engineering design guides published in New Zealand[35] and Australia.[41]

Documentation and reporting: The final step in the process is the preparation of design documentation and equipment and installation specifications. Documentation should provide a clear record of the process, including assumptions, tools and methods used, and results, and will likely be an important factor in obtaining final approval of the design. References should be provided, as well. The documentation of the process should start with the agreed upon goals and objectives and continue through the final design approval process.

This eight step process is detailed in Reference 76 and the forthcoming book by Custer and Meacham.[79]

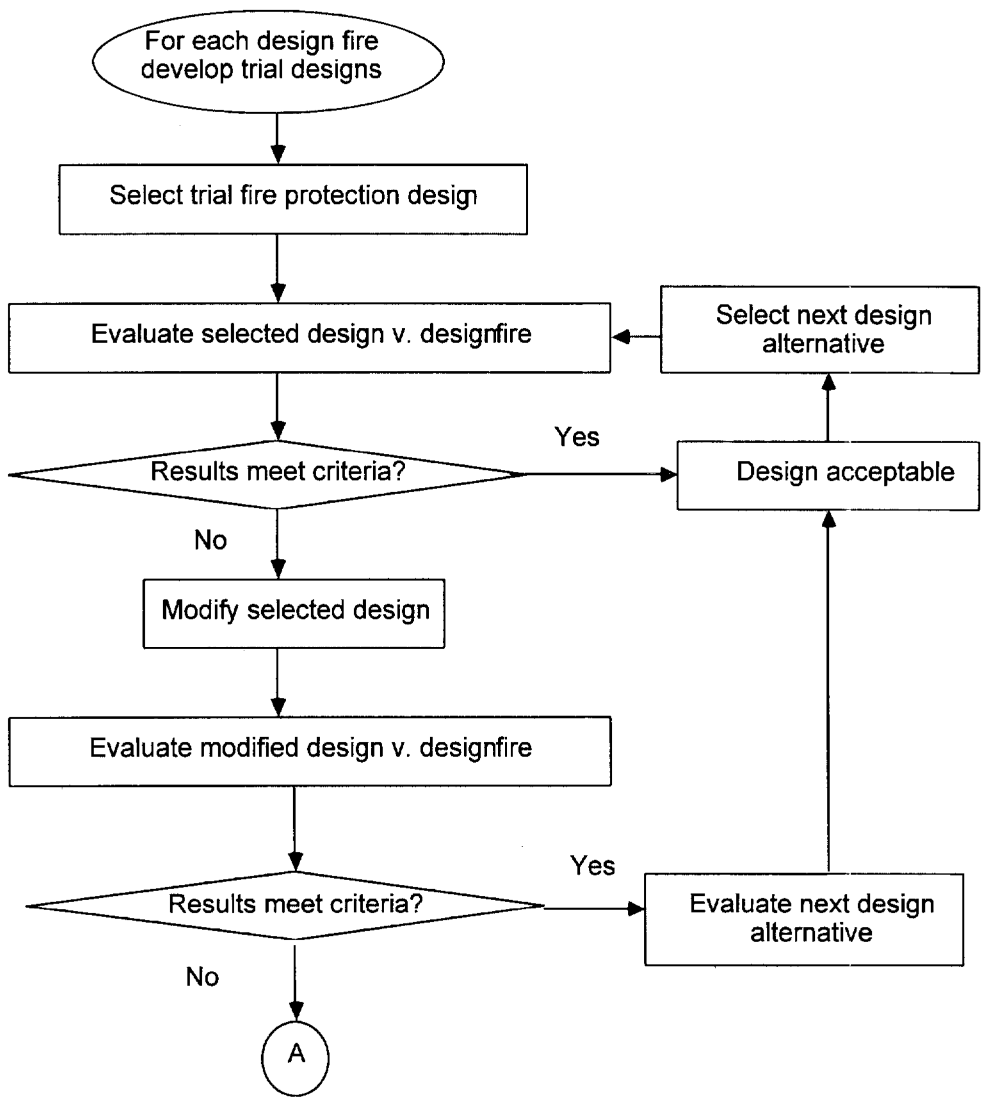

Figure 20 - Evaluation of Alternative Designs[74,76]

5.8.3 The Model Code Organizations and the National Fire Protection Association

Unlike the countries discussed thus far, the United States does not have a single nation-wide building code. Within the U.S., the upper tier of the building code structure is found in one of three "model" building codes which are adopted, more or less, on a regional basis. The three codes are (1) the *BOCA National Building Code*,[80] promulgated by the Building Officials &

Code Administrators International, Inc. (BOCA), which is used in the Mid-Atlantic, Mid-West and Northeast regions of the U.S.; (2) the *Southern Building Code*[81] (SBC), promulgated by the Southern Building Code Congress International (SBCCI), which is used in the southern portions of the U.S., and (3) the *Uniform Building Code*[82] (UBC), promulgated by the International Conference of Building Officials (ICBO), which is used in the western portion of the U.S. These model building codes are adopted at the state level and modified to meet local requirements. (There is also a level of regulations that are city/municipality specific.)

Another organization involved in the development of codes and standards is the National Fire Protection Association (NFPA), which is responsible for NFPA 70, *The National Electrical Code*,[83] NFPA 72, *The National Fire Alarm Code*,[84] and NFPA 101, *The Life Safety Code*.[55] Although *The Life Safety Code* is not a building code, it does include fire related building design criteria that are typically regarded as major components of a building code. In addition, *The Life Safety Code* is adopted in whole or in part in more states than any of the model building codes listed above.[85]

Although the U.S. lacks a national building code, there is a newly formed umbrella group, the International Code Council (ICC), that is composed of representatives of the three model building code groups (i.e., BOCA, ICBO, and SBCCI), whose purpose is to produce single, nation-wide plumbing, mechanical, fire and building codes for the United States.[86] Here again, the NFPA is expected to play a key role in that the NFPA is responsible for NFPA 70, *The National Electrical Code*, substantive portions of the Mechanical Code, and has a Fire Code as well. The current deadline for a single national fire code and a single building code for the United States is the year 2000.[86]

Even though the United States does not yet have a uniformly applied building code, prescriptive or performance-based, "performance" oriented wording does exist in U.S. codes and standards. As Lucht et. al. have written,[87] all of the model building codes in the U.S. allow for the use of "equivalent methods and materials." In essence, this means that an alternative to a prescriptive requirement can be submitted; if the building official determines that an equivalent level of safety is provided, the alternative may be accepted. Although this allows the use of innovative engineering and design techniques, the fact that these methods are acceptable only by exception (variance) and not by the "standard" approach makes them used much less often than they could be. In addition, it is not always clear what the code is seeking in terms of fire safety goals and objectives.

This situation is beginning to change. The NFPA, for example, has taken some definite steps in the direction of performance-based codes and standards. Several of the NFPA's existing standards, such as NFPA 72, *The National Fire Alarm Code*[84] and NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Spaces*,[88] contain wording and design methodologies that are performance-oriented. For example, NFPA 72 allows the designer to select heat detector spacing based on the design fire size or heat release rate to be detected within a compartment as an alternate to directly applying the rated spacing of the device. Similarly, NFPA 92B provides equations for estimating smoke-filling, smoke depth layer and other factors related to a design of smoke management systems for atria and large enclosed spaces.

To more deeply investigate the factors involved in a transition from prescriptive-based to performance-based codes and standards, the NFPA formed an in-house task group in early 1994. The task group's first report outlined a number of items that would need to occur to make the transition happen.[42] These include the development of specific goal and objective statements, development of performance criteria, identification of acceptable engineering tools and methodologies, and development of a means by which to verify that proposed designs are acceptable. Not surprisingly, these factors are quite similar to those identified by other countries discussed throughout this text.

The direction in which the NFPA is currently heading is a dual-track approach wherein the prescriptive code and the performance-based code co-exist. Within the NFPA's proposed approach, however, both the prescriptive approach and performance criteria will co-exist in the same document (not in separate documents as proposed for Canada). Under the dual-track approach, the design engineer can choose either the provided prescriptive approach or a performance-based approach, depending on the particular needs of the project. If a dual-track approach is adopted within the NFPA, the need for acceptable engineering tools and methodologies will become imperative.

The ICC has also begun moving towards performance codes with the establishment of a committee to develop a performance-based building code.[86] With their initial meeting planned for August 1996, it is anticipated that this committee will draft the "first" performance-based model building code for the United States.

5.8.4 The Federal Fire Safety Act

The first truly performance-based fire safety regulation with wide spread applicability in the United States was the "*Federal Fire Safety Act of 1992*."[30] In essence, the *Federal Fire Safety Act* requires sprinklers or *an equivalent level of safety* to be provided in certain types of Federal employee office and residential occupancies. (The Federal government is not required to abide by non-federal regulations, e.g., local or state regulations which include one of the model building codes.) The *Act* goes on to outline how equivalency may be determined, what the general procedures are, and who is qualified to determine equivalency. Although the *Act* only applies to certain Federal occupancies, it may serve as a springboard from which a more universal transition to performance-based codes is launched in the U.S.

Much of the detail of the *Act* can be found in Part 101-6, Miscellaneous Regulations, Sub-Part 101-6.6, Fire Protection (Fire Safety) Engineering.[30] When compared to other performance-based codes (such as those of England, Wales, or New Zealand), the Federal Fire Safety Act provides much more detail. In fact, the U.S. *Federal Fire Safety Act* is much like the Swedish regulations (discussed later in this Chapter). Whereas many of the other performance-based codes are all-encompassing regarding property protection, life safety, firefighter safety and the environment, the *Federal Fire Safety Act* is intended to "ensure the life safety of building occupants outside the room of fire origin." Furthermore, the *Act* specifically states that "the equivalent level of safety regulation in this sub-part does not address property protection, business interruption potential or firefighter safety during fire fighting operations."

This type of wording provides very clear guidance for the design engineer in setting design goals and objectives. Furthermore, definitions for specific criteria are provided. For example, "Flashover means fire conditions in a confined area where the upper gas layer temperature reaches 600 °C (1100 °F), and the heat flux at floor level exceeds 20 kilowatts per square meter (1.8 BTU per foot square per second)."[89]

The *Act* further goes on to indicate that, "To be acceptable, the analysis must indicate that the existing and or proposed safety systems in the building provide a period of time equal to or greater than the amount of time available for escape in a similar building complying with the Act." Although the *Act* does not specify how such an analysis is to be performed, it does provide specific criteria against which any analysis can be evaluated. As such, this is very much a performance or objective oriented regulation.

5.8.5 The Fire-Induced Vulnerability Evaluation (FIVE) Methodology

One of the first widely used performance-based approaches to fire safety analysis and design available in the United States is the *Fire-Induced Vulnerability Evaluation* (FIVE) *Methodology*.[31] Developed as a screening technique for fire analyses in U.S. nuclear power generating facilities, the *FIVE Methodology* consists of a computer program, worksheets and look-up tables that are designed to help fire protection personnel in nuclear power plants evaluate the potential for exposure fires to cause critical damage to essential safe-shutdown equipment. It is based on 'conservative' assumptions, using industrial and plant-specific databases for evaluating fire event sequences, and uses fire hazard models based on fundamental mass and energy conservation equations and empirical or semi-empirical correlations for heat and momentum transfer. Worksheets are used to help assess the impact on targets (i.e., combustibles, essential equipment, etc.) relative to various exposure fire sources (temperature and heat flux criteria are used). The basic approach is illustrated in Figures 21 and 22.

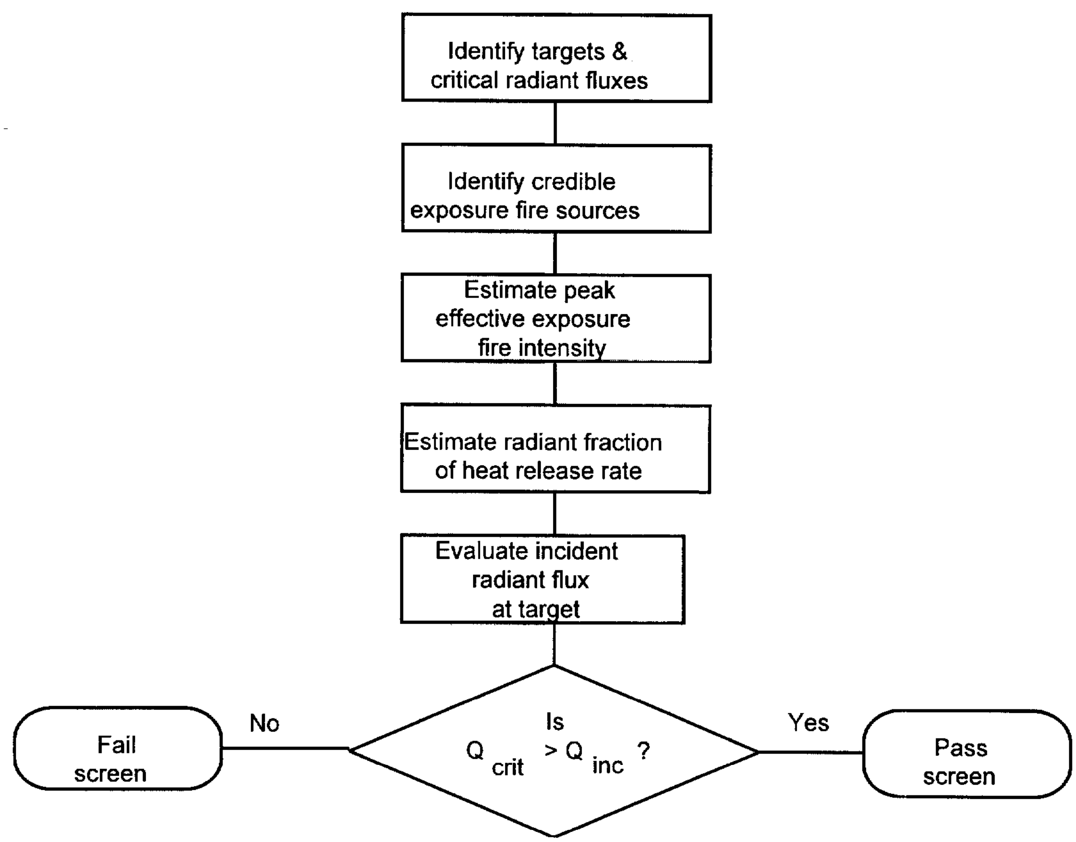

Figure 21 - Fire Screening Methodology - Thermal Radiation Scenarios[30]

Targets locations considered include above the fire source, within the hot gas layer (but outside of the plume) and lateral from the fire source. The look-up tables address fire-induced conditions in terms of a fire plume/ceiling jet stage, an unventilated smoke filling period and a ventilated quasi-steady burning period. Guidance is given on such areas as development of fire scenarios, damage threshold criteria (primarily for electrical cables) and exposure fire characteristics (i.e., design fires).

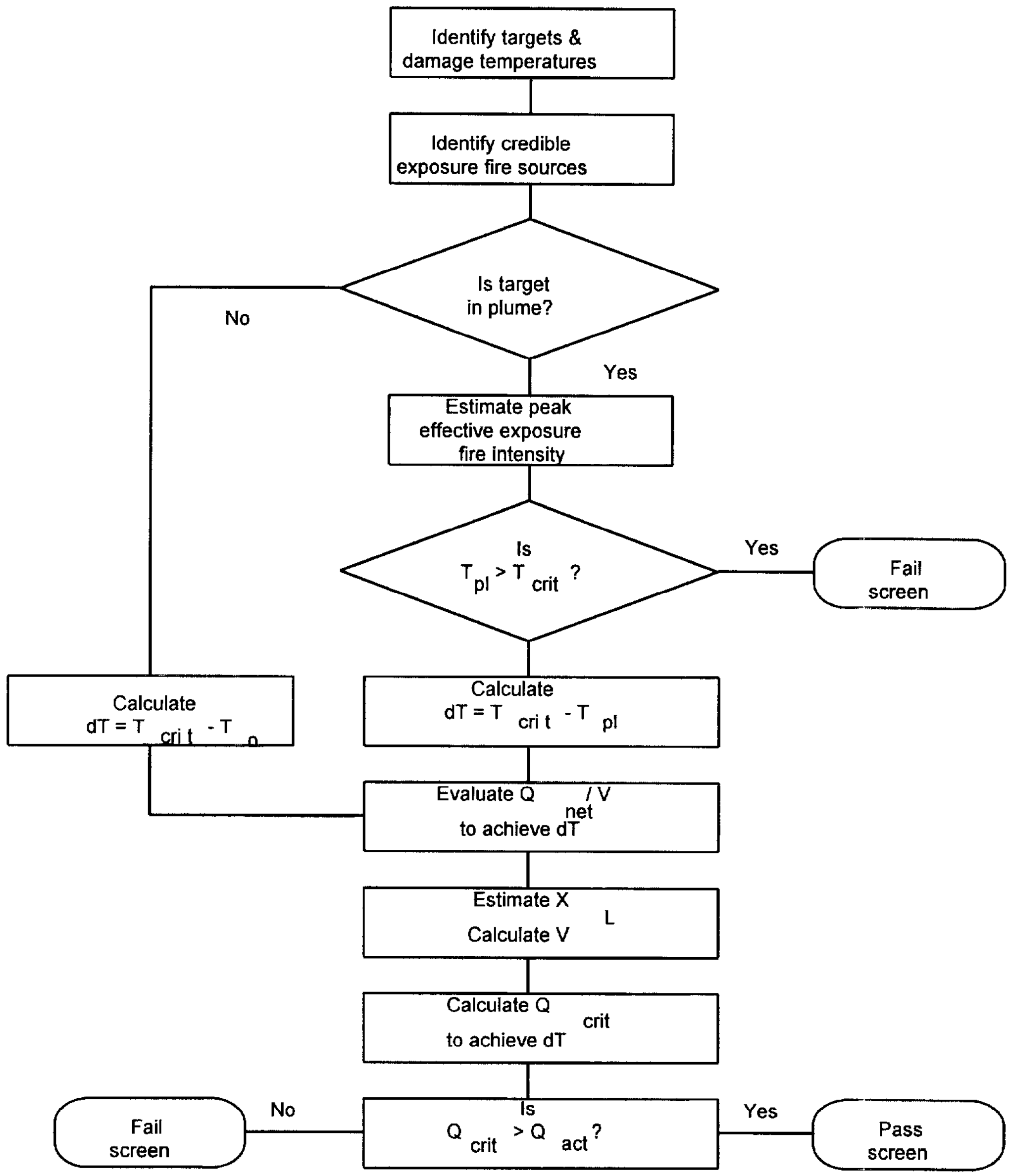

Figure 22 - Fire Screening Methodology - Hot Gas Layer Scenarios[30]

Although the *FIVE Methodology* was developed for the nuclear power industry, the concepts upon which it is based are relevant to the wider practice of performance-based fire safety analysis and design. In transferring the concepts to non-nuclear facilities, however, one should take care to understand the fundamental assumptions and criteria, and how they may or may not apply to the facility/situation under review.

5.7.6 Activities of the Society of Fire Protection Engineers

As building and fire code developers in the United States began looking towards performance-based codes and standards in the mid 1990s, it became apparent that a widely accepted, uniform framework for applying fire safety engineering principles to building analysis and design was needed. It also became apparent that appropriate and acceptable engineering tools and methodologies need to be available for fire safety design under a performance-based code structure.

To assist the fire and building communities in the U.S. in these regards, the Society of Fire Protection Engineers (SFPE), in 1995, began to facilitate the identification, evaluation and implementation into practice of emerging fire safety engineering tools and methodologies. The Society of Fire Protection Engineers, established in 1950, is an international professional society for engineers involved in fire protection (fire safety) engineering. Headquartered in the United States, the SFPE has chapters around the world, including Australia, Canada, France, Italy, New Zealand and Sweden. The mission of the SFPE is to advance the art and science of fire protection engineering. This is an ongoing mission that involves a variety of technology transfer, education and professional development activities that support the discipline of fire protection engineering internationally.

To help increase awareness of performance-based codes and fire safety engineering, the Society of Fire Protection Engineers utilizes two periodic publications: the *SFPE Bulletin* and the peer-reviewed *SFPE Journal of Fire Protection Engineering*. The *Journal* has been instrumental in providing international perspectives on performance-based codes and design methods, as well as discussing developments in these areas that have been made in the United States. This has helped the fire protection engineering community gain a basic understanding of the legal, regulatory and technical issues involved and challenges to be faced. Similarly, the *Bulletin* has provided timely articles on advancements in research and status of performance-based codes world-wide.

The SFPE also provides the primary reference document for performance-based design methods: the *SFPE Handbook of Fire Protection Engineering.*[23] When the first edition was published in 1988, the *Handbook* offered a one-of-a-kind compilation of quantitative calculation methods for solving fire safety engineering problems. Although similar documents have since followed, the *Handbook* remains a primary reference resource for fire safety engineers world-wide (referenced in the Fire Engineering Design Guide of New Zealand, the Fire Engineering Guidelines of Australia, the BSI Draft for Development on the Application of Fire Engineering Principles to Building Fire Safety Design in the U.K., and the draft ISO fire engineering guidance document under development). The original material has been updated and supplemented in the second edition (1995) with the latest methods for performing risk assessment, hazard analyses and design calculations, including new chapters on the use and application of computer fire models.[90]

In addition to the variety of publications mentioned above, the Society of Fire Protection Engineers provides engineering seminars, symposia, conferences and short courses on topics relating to performance-based codes and fire safety engineering. Two of the most recent courses have been focused entirely towards performance-based design: Performance-Based Design of Detection & Signaling Systems: A Tutorial for Engineers, and Introduction to Performance-Based Design for Fire Protection Engineers.

The SFPE has also undertaken projects to develop engineering practice (guidance) documents and to evaluate engineering tools and methodologies needed for successful implementation of a performance-based system in the United States. To successfully implement any new system or process into use, all of the components must be in place. In a performance-based code system, one needed component is that of engineering practice documents. The goal for the Engineering Task Group (ETG) on Engineering Practices is to begin developing a range of engineering practices for the fire protection engineering community. These documents will help fire protection engineers and regulatory officials understand the process to be taken, the engineering tools and methodologies available for use within the process and how to apply the engineering tools and methodologies with confidence. The first task of this group will be to develop a document on thermal radiation hazard calculations.

An engineering practice document is a framework or guidance document that establishes appropriate process and procedure for undertaking an engineered approach to a problem. In structural engineering, an example might be a manual for calculating the required strength of steel in building construction. In such a manual, acceptable methods of calculating the appropriate stresses and strains would be provided, and the engineer would select appropriate methods of calculation based on the specifics of the design situation. In fire safety engineering, such manuals are few and far between. Although several exist for calculating the fire resistance of structural members, few exist for calculating fire growth rate, radiation hazard potential or time to fire detector activation, for example.

The SFPE has also begun evaluating engineering tools and methodologies through the formation of an Engineering Task Group on Computer Model Evaluation. The goal for the ETG on Computer Fire Model Evaluation is to evaluate computer models, intended for use in fire safety engineering, on their applicability, use and limitations within the evaluation and design processes. It is doing this by stating the intended use of the model (from the model documentation) and evaluating the model and its documentation against its intended function. (It is not the intent to compare different models to each other.)

To minimize duplication of efforts in the area of developing evaluation methods for computer models, the ETG on Computer Fire Model Evaluation is applying various ASTM guides, i.e., ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Fire Models,[91] ASTM E 1472, Standard Guide for Documenting Computer Software for Fire Models,[92] and ASTM E 1591, Standard Guide for Data for Fire Models.[93] Additional evaluation criteria and procedures will be used and/or developed as necessary. The evaluations will be published in the form of reports that will provide an overview of the evaluation results and provide information to assist fire protection engineers and authorities having jurisdiction in determining if a specific model is appropriate for an intended application. Information regarding requirements for input data, limitations of the model and similar application-oriented information will also be included.

The Society of Fire Protection Engineers also saw the need for the fire and building communities to share a fundamental understanding and conceptual agreement about what performance-based fire safety codes and performance-based fire safety design mean in the United States.[44,94] To discuss and debate these issues, the SFPE convened a focus group consisting of key representatives of the fire and building communities in 1996. The concepts introduced and discussed in this text were the primary basis of discussion for this group.

6.0 Summary and Conclusions

A brief history of the evolution of performance-based codes and performance-based fire safety analysis and design methodologies has been presented. This discussion has included regulatory documents, detailed engineering analyses, stochastic and deterministic models, and methods to determine equivalencies to prescriptive code requirements. The analysis and design methodologies presented can be categorized as follows:

Combination Stochastic (Probabilistic) and Deterministic

- Beck, VUT (Australia) - computer model (stochastic and deterministic)
- *FiRECAM* (NRC, Canada) - computer model (stochastic and deterministic)
- *FRAMEworks* (NFPRF, USA) - computer model (stochastic and deterministic)
- *BFSEM* (Fitzgerald, USA) - framework document (uses subjective probability)
- *Fire Engineering Guidelines* (FCRC, Australia) - framework document
- *The Application of Fire Performance Concepts to Design Objectives* (ISO, International) - framework document (probabilistic approach not well developed)
- Draft for Development on the *Application of Fire Safety Engineering Principles to Building Fire Safety Design* (BSI, UK) - framework document (probabilistic approach not well developed)
- *Fire-Induced Vulnerability Evaluation (FIVE) Methodology* (EPRI, USA) - computer model and framework document (stochastic and deterministic, developed for use in nuclear power facilities)

Deterministic (Predominantly)

- *Fire Engineering Design Guide* (New Zealand) - framework document
- Engineering Evaluation of Building Fire Safety (CIB, International) - no document yet

Equivalencies

- *Total Fire Safety Design System for Buildings* (Japan) - equivalency to the Building Standards Law
- *Fire Safety Evaluation System* (NFPA, USA) - equivalency to the *Life Safety Code*

Despite the presence of this extensive list of methodologies from around the world (as well as those not included), there is not yet a single, generally accepted framework within the fire and building community for undertaking a performance-based approach to building fire safety analysis or design. This is due to a number of factors, including the complexity or simplicity of the methodology, the lack of data (probabilistic and deterministic), the lack of credible analysis and design tools, or the relationship of the methodology to a specific regulation. However, one can clearly see that a number of commonalties exist, and could conclude that the following list embodies the minimum features of a performance-based approach to fire safety analysis and design:

- There is a need to consider the level of acceptable risk (personal and societal).
- There is a need for clear specification and agreement of fire safety goals and objectives.

- There is a need for clear specification and agreement of performance (design) criteria.
- There is a need to understand how fire initiates, develops and spreads.
- There is a need to understand how various fire safety measures (active and passive) can mitigate potential fire losses.
- There is a need to understand how people react in a fire situation.
- There is a need to apply credible tools and methodologies in the determination of the above factors.
- There is a need to consider the financial impact of fire safety decisions.

Given these common goals, it should be possible to develop framework for performance-based fire safety analysis and design that is universally useable and acceptable. That is one of the primary motivations behind this NIST supported effort: to identify concepts of performance-based fire safety analysis and design, and to describe a simplified framework for undertaking such analyses and designs that can be universally applied by a designer or by a reviewer.

The approach described by Custer and Meacham,[78] which focuses on identifying or developing specific fire safety goals and performance objectives, within or outside of a performance-based regulatory structure, and describes steps to demonstrate that the resultant design meets the agreed upon goals and objectives, provides a framework that appears to fit the needs. It does not focus on equations, but rather the ability to (1) understand the concepts of performance-based design, fire safety goals and performance objectives; and (2) to apply the process of performance-based fire safety analysis and design based on sound fire science and engineering principles.

Finally, there is also a need to address uncertainties related to fire safety engineering, to the various analysis and design methods used for building fire safety design, and to the risk perceived by society by the use of these methods. There is uncertainty in performance-based fire safety engineering, as in any engineering process, because all is not known about the materials and systems one uses, nor how things may change in the future. (The adjustment of Q'_{crit} (or t_{crit}) to provide a factor of safety, for example, is a means to address uncertainties related to fire and performance-based fire safety engineering.) However, in order to accurately model or predict material or system response, and thus engineer an appropriate solution, it is important to be able to identify and address the uncertainties. Fire safety engineering lags behind other engineering disciplines in this area.

If these items can be adequately addressed so regulatory officials can be confident in the use of performance-based fire safety design methods, the widespread use of performance-based codes and fire safety design methods can be realized.

7.0 References

[1] The Building Regulations, Department of the Environment, London, England, 1985.

[2] Ministry of Construction, *Kentikubutsu no Sogu Koka Sekkeihov (Total Fire Safety Design System of Buildings),* the Building Center of Japan, Tokyo, Japan, 1989.

[3] *Project Report* and *Technical Papers, Books 1 and 2,* Fire Safety Engineering Project, The Warren Centre for Advanced Engineering, The University of Sydney, Sydney, Australia, December 1989.

[4] Pettersson, O., et al, *Bulletin 52,* Lund University of Technology, Lund, Sweden, 1976.

[5] Meacham, B. J., *International Development and Use of Performance-Based Building Codes and Fire Safety Design Methods*, SFPE Bulletin, March/April 1995.

[6] General Services Administration, *Technical Papers Given at the April, 1971 International Conference on Firesafety in High-Rise Buildings,* GSA, Washington, DC, April 1971.

[7] General Services Administration, *Technical Papers Given at the April, 1971 International Conference on Firesafety in High-Rise Buildings,* GSA, Washington, DC, November 1971.

[8] General Services Administration, *Building Fire Safety Criteria, Appendix D: Interim Guide for Goal-Oriented Systems Approach to Building Firesafety*, GSA, Washington, DC, 1972.

[9] NFPA 550, *Guide to Systems Concepts for Fire Protection,* National Fire Protection Association, Quincy, MA, USA.

[10] Personal communication, Robert W. Fitzgerald.

[11] *Program for Developing and Implementing a New Approach to Designing Fire Safety in Buildings,* U.S. National Academy of Science, 1975.

[12] Harmathy, T.Z., "Design Approach to Fire Safety in Buildings," *Fire Technology,* 12 (2): 95-108, 1976.

[13] Beck, V.R., "Performance-Based Fire Safety Design--Recent Developments in Australia," *Proceedings of the Technical Conference "Fire Safety by Design: A Framework for the Future,"* Fire Research Station, Borehamwood, UK, 10 November 1993.

[14] Kobayashi, M., *A Methodology for Evaluating Fire/Life Safety Planning of Tall Buildings, an Evaluation of Fire Safety in Buildings,* Occasional Report of the Japanese Association of Fire Science and Engineering, No. 3, Nikon Kasaigakka, pp.204-214, 1979.

[15] *Systems Methodologies and some Applications Symposium,* SFPE and University of Maryland, College Park, MD, 27-29 February 1980.

[16] *Engineering Applications of Fire Technology Workshop,* SFPE and National Bureau of Standards, NBS, Gaithersburg, MD, 16-18 April 1980.

[17] NFPA 101, *Life Safety Code,* Appendix C, National Fire Protection Association, Quincy, MA, USA, 1981.

[18] *Symposium on Quantitative Methods for Life Safety Analysis,* SFPE, University of Maryland, College Park, MD, 5-7 March 1986.

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

[20] Beck, V.R. and Yung, D., "A Cost-Effective Risk-Assessment Model for Evaluating Fire Safety and Protection in Canadian Apartment Buildings," *Journal of Fire Protection Engineering,* Vol. 2, No. 3, pp.65-74, 1990.

[21] Beck, V.R. and Yung, D., "Building Fire Safety Risk Analysis," *SFPE Handbook of Fire Protection Engineering,* Section 5, Chapter 11, SFPE/National Fire Protection Association, Quincy, MA, USA, 1995.

[22] *Symposium on Techniques of Quantitative Fire Hazard Analysis,* SFPE, University of Maryland, College Park, MD, 4-6 March 1985.

[23] *SFPE Handbook of Fire Protection Engineering,* 1st Edition, Society of Fire Protection Engineers & National Fire Protection Association, Quincy, MA, USA, 1988.

[24] Beck, V.R., et. al., *Draft National Building Fire Safety Systems Code,* Department of Industry, Technology and Commerce, Canberra, Australia, May 1991.

[25] Fowell, A.J., "International Standards Organization: Current Activities in Fire Safety Engineering," *Extended Abstracts of the SFPE Engineering Seminars, Issues in International Fire Engineering Practice*, Orlando, FL, USA, pp.29-32, 24-26 May 1993.

[26] Lucht, D., Ed., *Proceedings of the Conference on Fire Safety in the 21st Century,* Worcester Polytechnic Institute, Worcester, MA, 8-10 May 1991.

[27] Custer, R.L.P. and Meacham, B.J., *Performance-Based Fire Detection and Signalling Systems: A Tutorial for Engineers*, SFPE short course, Boston, MA, USA, 1992/93.

[28] *The Building Act 1991, The Building Regulations 1992,* New Zealand Government, Wellington, NZ, 1992.

[29] *The Fire Administration Authorization Act of 1992* (Public Law 102-522), Section 106, Fire Safety Systems in Federally Assisted Buildings, United States Fire Administration, (commonly referred to as the *Federal Fire Safety Act of 1992*), 1992.

[30] Mowrer, F.W., *Methods of Quantitative Fire Hazard Analysis*, Electric Power Research Institute, Report Number TR-100443 (distributed by SFPE, Boston, MA), 1992.

[31] Warrington Fire Research Consultants, *Draft British Standard Code of Practice for the Application of Fire Safety Engineering Principals to Fire Safety in Buildings,* Warrington, UK, 1993.

[32] CIB TG 11, Task Group documentation, International Council for Building Research and Documentation, 1994.

[33] CIB W14, Sub-Group on Engineering Evaluation of Building Firesafety, Working Commission Documentation, 1994.

[34] Swedish Board of Building, Housing and Planning, *Building Regulation* BFS 1993:57, Chapter 5 - Safety in Case of Fire (English translation), Stockholm, Sweden, 1994.

[35] Buchanan, A., *Fire Engineering Design Guide,* Centre for Advanced Engineering, University of Canterbury, Christchurch, New Zealand, July 1994.

[36] *Fire Code Reform Centre Limited,* Promotional Literature, Sydney, Australia, 1994.

[37] Custer, R.L.P. and Meacham, B.J., *Introduction to Performance-Based Design for Fire Protection Engineers,* SFPE short course, SFPE, Boston, MA, USA, 1994-1996.

[38] Australian Building Codes Board, *Draft Performance Building Code Australia,* Canberra, Australia, 1995.

[39] Canadian Commission on Building and Fire Codes, *Draft Strategic Plan,* CCBFC Strategic Planning Task Group, National Research Council, Ontario, Canada, September 1994.

[40] Nordic Committee on Building Regulations (NKB), Fire Safety Committee, *Performance Requirements for Fire Safety* and *Technical Guide for Verification by Calculation*, NKB, Helsinki, Finland, 1995.

[41] Fire Code Reform Centre, *Draft Fire Engineering Guidelines,* Sydney, Australia, March, 1996.

[42] *National Fire Protection Association's Future in Performance-Based Codes and Standards,* Report of the NFPA In-house Task Group, National Fire Protection Association, Quincy, MA, USA, July 1995.

[43] Tanaka, T., *The Outline of a Performance-Based Fire Safety Design System of Buildings,* Proceedings of the 7th International Research and Training Seminar on Regional Development Planning for Disaster Prevention, Improved Firesafety Systems in Developing Countries, United Nations Center for Regional Development, Tokyo, Japan, 1995.

[44] *Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States;* Phase I National Institute of Standards in Technology Grant No. 60NANB5DO138, Gaithersburg, MD, USA, in progress.

[45] NFPA 550, *Guide to Systems Concepts for Fire Protection,* National Fire Protection Association, Quincy, MA, USA, 1973.

[42] NFPA 550, *Guide to Systems Concepts for Fire Protection,* National Fire Protection Association, Quincy, MA, USA, 1974.

[47] NFPA 550, *Guide to Systems Concepts for Fire Protection,* National Fire Protection Association, Quincy, MA, USA, 1995.

[48] Fitzgerald, R.W., *Anatomy of Building Firesafety,* Worcester Polytechnic Institute, Worcester, MA, 1982.

[49] Fitzgerald, R.W., "An Engineering Method for Building Fire Safety Analysis ," *Fire Safety Journal*, Vol. 9, No. 2, p.233-243, July 1985.

[50] Watts, Jr., J.M., "Probabilistic Fire Models," Section 10, Chapter 10, *Fire Protection Handbook,* 17th ed., National Fire Protection Association, Quincy, MA, USA, 1991.

[51] Fitzgerald, R.W., *Building Fire Safety Evaluation Method,* Worcester Polytechnic Institute, Worcester, MA, 1993.

[52] Fitzgerald, R.W., "An Engineering Method for Translating Fire Science into Building Design," *Proceedings of the CIB W14 International Symposium and Workshops, Engineering Fire Safety in the Process of Design: Demonstrating Equivalency,* University of Ulster, Fire SERT Centre, Jordanstown, Northern Ireland, 13-16 September 1993.

[53] Fitzgerald, R.W., Richards, R.C. and Beyler, C.L, "Firesafety Analysis of the Polar Icebreaker Replacement Design," *Journal of Fire Protection Engineering,* Vol. 3, No.4, pp.137-150, 1991.

[54] NFPA 101A, *Guide on Alternative Approaches to Life Safety,* National Fire Protection Association, Quincy, MA, USA, 1995.

[55] NFPA 101, *Life Safety Code,* National Fire Protection Association, Quincy, MA, USA, 1993.

[56] Watts, Jr., J.M., "Fire Risk Ranking," *SFPE Handbook of Fire Protection Engineering,* 2nd Edition, Section 5, Chapter 2, National Fire Protection Association, Quincy, MA, USA, 1995.

[57] Ramachandran, G., "Stochastic Models of Fire Growth," *SFPE Handbook of Fire Protection Engineering,* 2nd Edition, Section 3, Chapter 15, National Fire Protection Association, Quincy, MA, USA, 1995.

[58] Law, M., "Fire Safety Design Practices in the United Kingdom - New Regulations," *Proceedings of the Conference on Firesafety Design in the 21st Century,* Worcester Polytechnic Institute, Worcester, MA, USA, 8-10 May 1991.

[59] Wakamatsu, T., "Fire Research in Japan - Development of a Design System for Building Fire Safety," *Proceedings of the 6th Joint Panel Meeting,* UNJR Panel on Fire Research and Safety, Tokyo, Japan, p.882, 10-14 May 1982.

[60] The Building Regulations, Department of the Environment, London, England, 1991.

[61] Cooke, G., "The Philosophy of Fire Engineering Being Developed by the British Standards Code Drafting Panel, *Proceedings of the CIB W14 International Symposium and Workshops, Engineering Fire Safety in the Process of Design: Demonstrating Equivalency*, University of Ulster, Fire SERT Centre, Jordanstown, Northern Ireland, 13-16 September 1993.

[62] Cooke, G. and Deakin, G., "Future Codes for Fire Safety Design," *Proceedings of the Technical Conference "Fire Safety by Design: A Framework for the Future,"* Fire Research Station, Borehamwood, UK, 10 November 1993.

[63] *Objective-Based Codes: A New Approach for Canada*, National Research Council, Institute for Reseach in Construction, Ottawa, Ontario, Canada, February 1996.

[64] Yung, D., "The Research Involved and the Development of the Procedures Related to Performance-Based Codes and Standards for the Canadian Building Codes," presented at the National Fire Protection Association Architects and Building Officials Section Meeting, Fall NFPA Meeting, Toronto, Ontario, Canada, November 1994.

[65] *Fire Code Reform Centre Limited,* Promotional Literature, Sydney, Australia, 1994.

[66] ISO/WD 13387, *The Application of Fire Performance Concepts to Design Objectives*, May 1995

[67] Magnusson, S.E., Franzich, H., and Harada, K., "Fire Safety Design Based on Calculations: Uncertainty Analysis and Safety Verification," Report 3078, Lund University, Lund, Sweden, 1995.

[68] *CIB W14 International Symposium and Workshops, Engineering Fire Safety in the Process of Design; Demonstrating Equivalency*, University of Ulster, Fire SERT Centre, Jordanstown, Northern Ireland, 13-16 September 1993.

[69] Custer, R.L.P., Demerest, D., Dobson, P., and Donohue, J., "Detecting and Minimizing Potential Impacts from HVDC Valve Hall Fires," IEEE Transactions on Power Delivery, Vol. 7, Issue 1, January/February 1991.

[70] Meacham, B.J., "Fire Safety in Nuclear Facilities: A Performance-Based Approach," *Proceedings of the Post SMiRT Conference No. 6 on Fire Safety in Nuclear Facilities*, Heidelberg, Germany, 22-23 August 1993.

[71] Capaul, T., and Meacham, B.J., "Structural Fire Resistance Analysis of a Diesel Engine Driven Power Generating Plant: A Performance-Based Approach," Proceedings of the SFPE Engineering Seminars on Performance-Based Fire Safety Engineering, Phoenix, Arizona, November 1993.

[72] Custer, R.L.P., "Progress on Computer Modeling and Performance-Based Detection System Design in the United States," European Society for Automatic Alarm Systems, Duisberg, Germany, 14 January 1994.

[73] Custer, R.L.P., Meacham, B.J, and Wood, C.B., "Performance-Based Design Techniques for Detection and Special Suppression Applications," Proceedings of the SFPE Engineering Seminars on Advances in Detection and Suppression Technology, San Francisco, 18 May 1994.

[74] Custer, R.L.P., "Introduction to the Use of Fire Dynamics in Performance-Based Design," Proceedings of the SFPE Technical Symposium: Applications of Fire Dynamics, University of British Columbia, Vancouver, Canada, 10-11 July 1995.

[75] Schifiliti, R.P., Meacham, B.J., and Custer, R.L.P., "Design of Detection Systems," SFPE Handbook of Fire Protection Engineering, 2nd edition, National Fire Protection Association, Quincy, MA, 1995.

[76] Meacham, B.J., and Custer, R.L.P., "Performance-Based Fire Safety Engineering: An Introduction of Basic Concepts," Journal of Fire Protection Engineering, Vol. 7, No. 2, 1995.

[77] National Materials Advisory Board; Guidelines for Developing and Analyzing Fire Scenarios; Fire Safety Aspects of Polymeric Materials, Vol. 4: Fire Dynamics and Scenarios, National Academy of Sciences, Washington, DC, 1978, pp. 42- 56.

[78] Babrauskas, V., "Burning Rates," SFPE Handbook of Fire Protection Engineering, 1st edition, National Fire Protection Association, Quincy, MA, 1988.

[79] Custer, R.L.P., and Meacham, B.J., Introduction to Performance-Based Fire Safety Design, Society of Fire Protection Engineers (in press), 1996.

[80] *The BOCA National Building Code/1993*, Building Officials & Code Administrators, Country Club Hills, IL.

[81] *Southern Building Code*, Southern Building Code Congress International Inc., Birmingham, AL.

[82] *Uniform Building Code*, International Conference of Building Officials, Whittier, CA.

[83] NFPA 70, *The National Electrical Code*, National Fire Protection Association, Quincy, MA, USA, 1994.

[84] NFPA 72, *The National Fire Alarm Code*, National Fire Protection Association, Quincy, MA, USA, 1994.

[85] Private communication, Casey Grant, National Fire Protection Association, 1996

[86] *International Code Council*, Country Club Hills, IL

[87] Lucht, D.A., et. al, "International Developments in Building Code Concepts, *Journal of Fire Protection Engineering,* Vol 5, No 4, 1993, pp125-133

[88] NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria and Large Areas*, National Fire Protection Association, Quincy, MA, USA, 1991.

[89] *General Services Administration, 41 CFR Part 101-6 (FPMR Amendment A-52*), Federal Register, Vol 59, No 210, 1 November 1994.

[90] *SFPE Handbook of Fire Protection Engineering,* 2nd Edition, Society of Fire Protection Engineers & the National Fire Protection Association, Quincy, MA, USA, 1995.

[91] ASTM E 1355, *Standard Guide for Evaluating the Predictive Capability of Fire Models,*

[92] ASTM E 1472, *Standard Guide for Documenting Computer Software for Fire Models,*

[93] ASTM E 1591, *Standard Guide for Data for Fire Models,*

[94] Meacham, B.J., *Performance-Based Codes and Fire Safety Design Methods: Perspectives and Projects of the SFPE*, proceedings of Interflam '96, Interscience Communication Ltd, London, 1996.

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Brian J. Meacham
Society of Fire Protection Engineer
Bethesda, MD 20814

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This document provides an overview of the evolution of performance-based building codes and performance-based fire safety analysis and design methods. It was developed during the period of September 1995 through August 1996. Section 2 provides a chronological overview of the evolution of performance-based codes and performance-based fire safety analysis and design methods from the 1970s through the present. Sections 3 through 5 detail the efforts undertaken in both code development and analysis and design method development during the 1970s, 1980s and 1990s respectively. The summary provides a list of analysis and design methods by type, and provides some thoughts on where future effort might be beneficial. Although sufficient detail is provided for the reader to gain an understanding of the fundamental principles behind the various codes, fire safety analysis methods, and fire safety design methods in use or in development as of July 1996, it is highly recommended that the reference documents be consulted for more detailed information. This report is a reprint of a document originally published by the Society of Fire Protection Engineers in August 1996. Although minor editorial modifications have been made, no updates have been included to reflect those advances in the areas of performance-based codes and fire safety design methods that have been made since 1996.

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