*Invited Lecture*

# International Experience in the Development and Use of Performance-Based Fire Safety Design Methods: Evolution, Current Situation and Thoughts for the Future

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## ABSTRACT

Over the past fifty years, fire safety engineering* has grown and developed into an accepted, if not fully mature, engineering discipline. This has been possible for a variety of reasons, including an ever-increasing understanding of fire safety science, continuing development of analytical methods for engineering analysis and design, technological advances in computational tools, and the global movement towards performance-based building and fire regulations. This paper reviews the current state of fire safety engineering by looking at international experiences in the development and use of performance-based fire safety design methods. It discusses the impact of increasing scientific knowledge and the evolution of performance-based fire safety design methods and regulations, and it speculates on what will be required for fire safety engineering to reach maturity as an engineering discipline.

**KEY WORDS:** Performance-based fire safety design, fire safety engineering, performance-based building regulations

## INTRODUCTION

"Performance-based" has been the epithet of the 1990s throughout the fire safety community. It seems that one cannot open a fire-related journal, set of proceedings, or other publication without finding reference to performance-based codes, performance-based fire

* As used in this paper, the term "fire safety engineering" is synonymous with the terms "fire engineering" and "fire protection engineering," and is defined as the application of science and engineering principles to protect people and their environment from fire.

safety design, or some derivative thereof. Why is this so? What has driven the fire safety community to search for means and methods to measure, analyze, describe, and predict performance? In many respects, the movement to performance-based analysis and design is part of the natural evolution of an engineering discipline. By one definition, engineering is the art or science of making practical application of the knowledge of pure science [1]. As the knowledge base grows, the horizon for practical application of the knowledge increases accordingly. When this knowledge base includes understanding how materials, systems, and buildings perform under a variety of conditions, it opens the door to performance-based analysis and design. This can be seen by reviewing the development of an allied profession.

## THE IMPACT OF INCREASING SCIENTIFIC KNOWLEDGE ON THE EVOLUTION OF PERFORMANCE-BASED STRUCTURAL ENGINEERING

Consider structural engineering. For centuries, most structures were built of wood, masonry, concrete and other natural materials because these materials were readily available and people had some knowledge about their properties and how to build with them. However, a comprehensive technical understanding of material properties and forces acting on structures did not exist. As a result, although these materials were used to build some rather large structures, such as the Parthenon and the pyramids of Egypt, the size of structural elements and the height of the structures were restricted. Lack of technical knowledge and modern materials prevented builders in earlier times from erecting structures common today, such as high-rise office buildings [2]. In short, the analytical tools were lacking to understand and predict the performance of buildings, as is routine today.

However, beginning with the works of Newton and Hooke in the late 1600s, and continuing with the work of Cauchy, Euler, and Young in the early 1800s, a scientific knowledge base on properties of materials and their reaction to forces was forming [2]. By the mid-to-late 1800s, and continuing into the early 1900s, such advances in scientific understanding, and their conversion to practical applications, led to the realization that other materials could be used, in some cases more effectively, in the building of structures. Examples from the time period include the introduction of steel frame and reinforced concrete construction; materials still widely used today.

The knowledge base that led to the widespread use of these materials accumulated over several years, and was fed by the efforts of researchers in a variety of disciplines. Furthermore, the research did not stop when new applications were realized at the end of the 19th century, but rather, became more focused at addressing unknowns and uncertainties in the technology and the knowledge base. In the late 1800s and early 1900s, when new structural steel applications were being tried, using the new understanding of forces and strengths of materials, there was the realization that uncertainty needed to be addressed. For the construction of important structures such as bridges, British and American engineers began performing strength calculations. These included calculating the "highest possible tensile" stresses in the structure, using the methods of the time, and ensuring these stresses were less than the "official tensile strength" of the material. Knowing that they did not have a complete understanding of highest possible stress or strength, the engineers made the highest calculated working stress significantly less, as much as seven or eight times less, than the strength of the material as determined by breaking a simple, smooth, parallelstemmed test piece [2]. This was known as "applying a factor of safety," and at the time, any attempt to save weight and cost by reducing the factor of safety was considered a recipe for disaster.

This approach of applying factors of safety was carried over into building codes, and was widely applied to structural components, such as beams and columns. In the early 1900s, such factors of safety were often in the range of three to four. In essence, these values were used because they were known to work: no analytical methods were applied to derive them. As more knowledge about materials was gained, and better analytical tools were developed, the structural engineering community began decreasing the factors of safety specified in design standards and codes of practice. This is evident in the Load and Resistance Factor Design (LRFD) approach widely used today [4,5,6].

## THE IMPACT OF INCREASING SCIENTIFIC KNOWLEDGE ON THE EVOLUTION OF PERFORMANCE-BASED FIRE SAFETY ENGINEERING

Fire safety has been a concern for as long as people have been building and inhabiting structures. This is especially true in urban areas where the threat of conflagration is highest, as evidenced by regulations to minimize the likelihood of conflagration enacted following the fire of London in 1666. However, the methods used to mitigate unwanted fires changed little from that time until the early part of this century. Much like the structural engineering situation, a comprehensive technical understanding of fire was lacking, and people generally relied on experience as a guide.

By the middle-to-late 1800s, however, advances in scientific knowledge and the industrial revolution created new challenges for fire safe design. New materials were being developed whose burning characteristics were not well known; new mechanical technologies, such as steam and internal combustion engines, presented explosion and fire hazards, and new structural technology enabled larger and taller buildings to be constructed. In addition, more and more people began moving from the countryside into growing cities. As a result of these factors, large life-loss and large monetary-loss fires became a characteristic of the early 20$^{th}$ century. The magnitude of the problem for the United States is well represented by data that show the ten deadliest fires occurred between 1865 and 1947, with six of the ten largest fire losses (in millions of dollars) occurring during the same period [6].

The reaction to the fire problem in the early part of this century was not, as in structural engineering, primarily motivated by increasing technical knowledge,[†] but was motivated by societal concern, resulting in controls imposed through regulation; and by economic losses, prompting research by industry and the insurance community. Large life-loss fires in the early part of the century prompted the development of building and fire codes and standards, including the first edition of NFPA 13, *Installation of Sprinkler Systems* [7], in 1896, the establishment of the NFPA Committee on Safety to Life in 1913 [8], and the first edition of the Uniform Building Code in 1927 [9]. Unlike the changes ongoing in the structural community, however, the provisions being enacted in the fire community were primarily prescriptive in nature, identifying what, where, and how some system or feature was to be installed, with little emphasis on how the building should perform overall.

[†] Of course, the desire to build larger buildings was economically motivated as well.

Nonetheless, the motivation to develop and enact building fire safety codes and standards for safety to life, and to develop strategies and technologies to minimize contents and property damage due to fire, began a period of scientific investigation of fire and fire properties of materials. An indication of this can be seen in a submittal letter for a U.S. Department of Commerce Building Code Committee report on fire resistance dated August 21, 1930 (*sic*) [10]:

> In searching for test data to serve as a basis for conclusions the committee has been impressed by the fact that the science of fire protection is in a stage of development as compared with the knowledge of other properties of materials and constructions. The program of tests under way and contemplated by the Bureau of Standards has advanced this science very greatly.

In the years that have followed, fire safety science research around the world has provided the fire safety engineering profession with an ever-increasing understanding of fire phenomena, of the fire performance of materials, and of the impact of fire on people, property, business continuity, and the environment. Building on the seminal works of such pioneers in fire research as Kawagoe, Thomas, Emmons, and Rasbash, great strides were made in gaining fundamental scientific knowledge of fire safety science from the 1950s through the 1980s. One needs only review the past proceedings of the symposia of the International Association for Fire Safety Science, the *SFPE Handbook of Fire Protection Engineering*, or such technical journals as *Fire Safety Journal* to see the evidence of this.

As research and loss experience increased the technical understanding of fire and its impacts, it became apparent that fire and fire impacts could be estimated or predicted. This realization provided an impetus to the fire safety engineering community to look at methods to predict fire and its impacts instead of simply designing fire mitigation measures as they had in the past. To make this happen, the fire safety engineering community relied on the research community, which had collected data; developed correlations, analytical methods, and models to describe fire initiation, growth, and spread; and developed analytical methods and models to predict possible fire impact. Although the fire safety engineering community welcomed the input from the research community, many found the available correlations, analytical methods, and models time-consuming to work with and not generally accepted by the building and fire authorities.

More recently, however, advances in computer technology led to the development of computer-based analysis and design tools for use by fire safety engineers. This resulted in a change to how fire safety problems were approached, as the once time-consuming analytical methods became faster and easier to use. As more of the computer-based analytical methods were used, some in the fire safety engineering community accepted them as tools for daily use, and began to advocate fire safety analysis and design using the computer-based analytical methods instead of the traditional codes- and standards-based design approach. In some respects, the increasing use and general acceptance of computer-based analytical methods within the fire safety engineering community has contributed to the movement to performance-based building codes and the concept of performance-based fire safety design [11]. As such, some people view "computer fire models" as synonymous with "performance-based design" (although the author would argue against such an interchange of terms), and some consider fire safety engineering to now be at a state of development parallel to structural engineering (the author would disagree with this as well).

However, there remain some critical differences in the states of development between fire safety engineering and structural engineering. Unlike structural engineering, fire safety engineering still lacks a common framework for evaluation and widely accepted analytical methods with known limits of uncertainty. Although significant effort has been aimed at developing a common framework over the past ten years, it does not yet exist in a comprehensive and integrated form. Such a framework is close at hand, however, and the next section will overview historical developments to date in this area. Of greater concern is the lack of understanding regarding the limits of uncertainty of the analytical methods, and more importantly, of the broader system within which one applies these methods.

## THE EVOLUTION OF A FRAMEWORK FOR PERFORMANCE-BASED FIRE SAFETY ANALYSIS AND DESIGN AND OF PERFORMANCE-BASED CODES

Much has been written about the evolution of performance-based fire safety design methods and codes [11,12], so an extensive treatment will not be provided here. Rather, only a brief overview of international activities in the development of performance-based fire safety design methods and codes will be provided, with detailed discussion offered on some key events of the past twenty-five years.

### Developments toward a Framework for Fire Safety Design

Systems and Risk-Based Approaches

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 [11]. In 1972, the U.S. General Services Administration and the U.S. National Bureau of Standards jointly developed an event logic diagram that 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,* became a fundamental document for describing a risk-informed systems approach to building fire safety design [13]. Major features 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 alternative fire safety systems to be compared.
- The use of probability to describe fire safety performance.

Following the publication of *Appendix D*, activities relating to risk-informed 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, which although modified over time, can still be found in NFPA 550, *Guide to the Fire Safety Concepts Tree* [14].

Another result from the GSA *Appendix D* work is the Fire Safety Evaluation System (FSES) used in NFPA 101A, *Guide on Alternative Approaches to Life Safety* (referred to hereafter as 101A) [15]. The FSES is a schedule approach to determining equivalencies to the NFPA 101 *Life Safety Code* for certain institutional occupancies [16]." It consists of a variety of fire safety parameters (such as construction, hazardous areas, manual fire alarms, automatic detection systems, and automatic sprinkler systems) for which designated point values have been developed. 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. It should be noted that the point values for the fire safety parameters and for the risk parameters were not based on scientific or statistical data, but were developed from the "experienced judgment of a group of fire safety professionals and represent the opinions of that panel of experts" [16]. For this reason, one should not transfer the point scheme to determine equivalency with other codes, or assume that the point scheme is valid outside of North America.

The development of the *Building Firesafety Evaluation Method* (BFSEM) also followed the publication of *Appendix D.* With its beginnings as a course taught by Rexford Wilson and Robert Fitzgerald [17], the BFSEM has grown into a systems approach to building fire safety analysis [18,19]. It uses a structured framework to guide the process of performance evaluation. 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, automatic and manual suppression, smoke spread, and occupant safety. A major attribute of the method is that one can compare different designs on a common basis. Fire related factors, like fuel load and arrangement, and fire protection features, like automatic and manual fire detection and suppression (including fire department response), integrity of barriers, and operation of emergency systems, are evaluated as to how the fire will develop and spread. This is accomplished through a combination of the framework, engineering judgment, and deterministic calculation methods. The way that the framework has been developed, the analysis can be done using one's knowledge and experience alone (e.g., an audit), with the additional use of analytical methods, and with the use of subjective or objective probabilities (from engineering judgment or statistical data, respectively).

Another key effort that began in the 1970s was the development of a risk assessment model by Beck [20,21,22]. The intent was to develop a system model that could identify cost-effective building fire safety design solutions that achieved an acceptable level of occupant fire safety. This required integration of a risk assessment model with various sub-models that addressed fire, human response, and the like. The risk assessment system model (the 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. The 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)*. These terms are defined in various publications on the model and its computerized form (CESARE-Risk) [22,23,24]. To calculate the expected risk to life and the fire cost expectation values, the computerized model, CESARE-Risk, considers interaction between fire growth, fire spread, smoke movement, human behavior, the response of building systems and the response of a fire brigade. The model uses specified design fires to characterize the broad spectrum of fires that could be expected in reality. As Beck 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 [23]. 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.

A similar computerized fire risk assessment model, FIRECAM, is currently being developed and evaluated in Canada. FIRECAM is based on the concepts developed by Beck (as outlined above), and although some differences exist in the sub-models, they are essentially the same will not be discussed here [24].

A still different type of approach to risk-informed fire safety analysis and design developed within the structural fire safety arena [25,26]. Using probability- and reliability-based design concepts developed in the structural engineering community, these approaches began by considering primarily the structural material, the likely fuel loading, and the likely time-temperature output of a fire, with explicit safety and reliability factors to account for uncertainties. Over time, the concepts that emerged from structural and other engineering disciplines have been applied to the entire building fire safety problem [27,28,29]. As discussed in a key publication on fire risk and uncertainty [27], fire safety engineering can benefit greatly not only from advances in structural reliability engineering, but from quantitative risk assessment (QRA) techniques used in chemical engineering and probabilistic risk assessment (PRA) techniques used in nuclear engineering as well. A central point is that risk-based design is useful in accounting for uncertainty and unknowns associated with data and with models: areas that fire safety engineering need to address.

Guidance (Framework) Documents

Toward the end of the 1980s and into the 1990s, work began on the development of guidelines for fire safety engineering that described the overall process and indicated how risk-based and deterministic-based methods could be used in addressing building fire safety concerns. Whereas many of the approaches described above focused on evaluation of building fire safety, or evaluation of risk, these documents intended to provide design guidance. The framework for many of these guidelines has its origins in outcomes of the Australian Warren Centre Fire Safety and Engineering project [30] and of the *Draft National Building Fire Safety Systems Code* [31]. The Warren Centre project brought 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. Two key outcomes were that risk assessment models should be used as a basis for identifying cost-effective combinations for fire-safety sub-systems for building design, and designers should adopt appropriate fire safety engineering techniques for the design of fire safety systems in buildings. Using these outcomes 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) [31]. A key feature of the Code was the use of sub-systems describing different aspects of the fire safety problem. (It is interesting to note that these sub-systems correspond nicely with those used by Fitzgerald.) Efforts to adopt and use the NBFSSC did not progress immediately, and it was not until the Fire Code Reform Centre (FCRC) was established in 1994 that work in the area of fire safety design picked up again in Australia. However, given the past work, it took little time to develop and publish one of the first fire engineering design guides currently in use today [32] (the New Zealand Fire Engineering Design Guide [33] preceded the Australian guidelines by about two years).

Although efforts to expand upon the NBFSSC slowed in Australia, groups developing fire safety engineering guides in the UK and within the International Organization for Standardization (ISO) adopted the concepts of the NBFSSC. In the early 1990s, UK fire safety engineering professionals set out to develop a code of practice that would promote the use of fire safety engineering principles in building design [34]. Over the next several years, a framework was developed that described the interactions of various fire safety sub-systems: fire growth and suppression, smoke spread, fire spread, detection, intervention, and evacuation. The result is the British Standards Institute (BSI) document DD240, Fire Safety Engineering in Buildings [35]. Although the intent was to develop a standard on fire safety engineering, the document was published as a draft for development, as concerns were raised over the current state of knowledge in fire safety engineering. The same intent and same result occurred within ISO TC92 SC4, a group whose aim was to develop an international standard for fire safety engineering. As with BSI DD240, however, it appeared that the state of knowledge was such that a standard could not yet be produced. Instead, ISO TR 13387, *The Application of Fire Performance Concepts to Design Objectives* [36], will be published as a technical report, and not a standard.

After reviewing the situation world-wide [11,37], the Society of Fire Protection Engineers (SFPE) has also developed a guide to performance-based fire safety analysis and design (one that resembles the Australian, British, ISO, and New Zealand guides) [38]. The fact that the SFPE guide resembles the other approaches indicates that the fire safety engineering community is close to having a common framework for fire safety analysis and design. The fact that there is not yet a single guide, however, indicates that shortcomings in still exist. This will be explored in some detail the final major section of this paper.

**Development of Performance-Based Building Regulations**

Although systems approaches to fire safety design were being developed in a number of countries by the mid-to-late 1980s, they were not being widely applied. This was due in part to the developmental stage of many of the approaches, as well as to the restrictions imposed by the building regulatory systems in use at the time. However, changes began occurring in the building regulatory arena in the late 1970s and early 1980s that helped promote the acceptance of, and give order to, the use of systems approaches to fire safety engineering. Changes in the building regulatory arena occurred for many reasons, including broad government deregulation and a desire to promote better exchange of technology and trade across national boundaries. To address these issues, many countries began transitioning to a performance-based building regulatory system and away from the traditional prescriptive-based system. The basis for many of the new systems was the five-level structure developed by the Nordic Committee on Building Regulations (NKB) [39,40]. The NKB structure is as follows:

Level 1: Goals – essential interests of the community at large (society) with regard to the built environment.

Level 2: Functional Requirements – qualitative requirements of buildings or specific building elements.

Level 3: Operative Requirements – actual (quantitative) requirements, in terms of performance criteria or expanded functional descriptions.

Level 4: Verification – instructions or guidelines for verification of compliance.

Level 5: Examples of Acceptable Solutions – supplements to the regulations with examples of solutions deemed to satisfy the requirements.

Perhaps most important to the fire safety engineering community are Levels 3 and 4: Operative (Performance) Requirements and Verification. If a building or a building element can be described in terms of how it performs, normally and under fire-induced load, and methods are available to verify this performance, a design solution that complies with the regulation can be engineered. This regulatory structure, and these realizations, provided additional motivation to explore how materials, systems, and people responded (performed) in various fire situations (scenarios), and to look at the concept of overall fire safety performance of buildings promoted by Nelson, Fitzgerald, Beck and others. The regulatory structure also provided a framework within which fire safety engineering could be applied.

Although the NKB structure served as a common model for building regulatory development, there was no common model for defining the performance of materials, systems, buildings, or people when subjected to fire effects. Fire tests continued to be more focused on the prescriptive-based regulatory system, and efforts with the International Organization for Standardization (ISO) to harmonize fire test methods were proceeding at a very slow pace. In addition, there were still few verification methods that had broad acceptance within the fire safety community. The lack of common definitions, test methodologies, and verification tools, among other non-technical issues, prompted different countries to adopt different regulatory approaches.

The Japanese Approach

In Japan, the Building Standards Law, a highly prescriptive building code system, had been in force since 1950. Although these regulations were deemed adequate in providing an acceptable level of fire safety, it was also felt that the prescriptive nature "incurred the undue increase of construction costs and restraint to building designs" [41]. Recognizing this situation, the Building Research Institute (BRI) of the Ministry of Construction (MOC) embarked on a five-year research project to develop a system where alternatives to the prescribed fire safety requirements could be demonstrated to be equivalent to the objectives of the Building Standards Law [41,42]. Although the project was successful, it was also recognized that the outcome was a system that focused on equivalency to the Building Standards Law, and that more could be accomplished if a performance-based system were developed. To address this concern, and to expand the application of performance-based fire safety design, the Ministry of Construction began a new project in 1993, "Development of an Assessment Method for Fire Performance of Building Elements" [41]. The aim of the new effort is not to describe how to design fire safety, but to define the requirements and standards with which buildings must comply. The format proposed for the new system is based on the Nordic 5-Level Model described above, and includes Objectives, Functional Requirements, Performance Requirements, Recognized Verification Tools, and Recognized Specification of Structure and Component (performance) [43]. Key aspects of the proposed system include multiple levels of performance standards (criteria) for verification, and built-in safety factors that consider the knowledge base and experience with various protection methods [41]. The performance standards (criteria) include performance-based (designated

P), complementary (C), deemed-to-satisfy (D), specification-based (S), and expert opinion (E) [44]. The P criteria are unique in that they may be some limit state, such as the heat to which escaping occupants are being subjected, expressed in terms of a computational formula to be solved from an analysis of the fire conditions. This approach couples the threshold performance criteria with a computational method, and does not permit the designer to select either independent of the regulation (i.e., all five levels of the NKB structure are included in the base regulation).

The Approach of England and Wales, New Zealand, and Australia

The situation in England and Wales began similarly, yet the results were quite different. Until 1985, the building regulations for England and Wales were largely prescriptive and rather restrictive. 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 [45]. This was made possible, in part, by applying the basic concepts of the NKB structure, using functional, or performance language instead of prescriptive requirements. However, unlike the approach taken in Japan, acceptance criteria and methods were not included in the regulation. This afforded engineers the opportunity to demonstrate compliance using performance/acceptance criteria, safety factors, engineering methods, and verification methods of their choice. 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) [46]. Thus, to gain acceptance for engineered solutions, efforts were undertaken to develop a fire safety engineering standard (the result of which is BSI DD240, as discussed earlier in this paper).

The transition to a performance-based regulatory system in Australia and New Zealand was similar to situation in England and Wales [11,47,48]. Shortcomings were seen with existing regulations, and more flexibility and better cost efficiency were seen as strong motivators to change the system. In both countries, the regulatory systems follow the NKB structure, with Levels 1, 2, and 3 in the regulations, and Levels 4 and 5 published separately from the building code as engineering guidance documents and approved documents.

The Situation in the United States

The situation in the United States is somewhat more complex, as slightly different approaches are being taken by the International Code Council (ICC) in the development of a performance-based building regulation, and by the National Fire Protection Association (NFPA) in the development of a performance-based Life Safety Code [11,49,50,51]. In brief, the ICC is trying to define performance in such a way as to avoid requiring the use of specific threshold values (e.g., upper layer temperatures, incapacitating carbon monoxide levels) for broad classes of buildings, compartments, and occupant characteristics. The concern is that with such a wide range of variability, the use of a specific value for a generalized class of buildings, compartments, or people, may result in an overly conservative design in some cases, and a potentially dangerous design in others. (A closer look to the Japanese approach may help in this regard.) The intent is to have the design engineers undertake appropriate analyses and select appropriate criteria, following the requirements of the code in consultation with the approving authority. Somewhat differently, the NFPA, is considering the inclusion of specific design fire scenarios and the referencing of guidance on Fractional Effective Dose (FED) as recommended tenability criteria, both of which may limit the design engineer's options if the specific project differs significantly from the cases the code developers considered [52]. Regardless of this dichotomy in regulatory approaches, the *SFPE Engineering Guide to Performance Based Analysis and Design* [38] is intended to be compatible with both.

## THOUGHTS ON THE CURRENT SITUATION AND THE WAY FORWARD

At the present time, fire safety engineering, often under the label "performance-based fire safety design," is being practiced around the world. Applications range from historic structures [53] to a pyramid-shaped casino with a volume of 595,000 cubic meters [54], from shopping centers and malls [55] to high-rise atria buildings [56], from apartment buildings to sports arenas, and from cleanrooms to power generating facilities [57]. Analyses performed range from egress times to time until structural failure, from sprinkler activation to smoke exhaust capacity, and from material control to fire department response. As discussed in the previous sections, this growing use of performance-based fire safety design concepts has been made possible due to advances in the scientific principles underlying fire and fire safety systems, the development of risk-informed systems approaches to fire safety analysis and design, and the implementation of performance-based regulations.

In many respects, the fire safety science and engineering community can be pleased with the current situation and progress to date. However, there is yet a long way to go. Consider the following summary of observations made by Cornell on the maturation of a newly emerging engineering area [58], and reflect on the current state of performance-based fire safety design described by this paper.

> In its earliest stages, a new area is characterized by uncoordinated relationships between practice and research, and between needs and solutions. Problems that have been addressed by researchers tend to reflect personal tastes, ease of formulation or solution, and simple chance. Those applications in practice that do exist tend to be small parts of larger problems, isolated and resolved without reference to a broader framework because the framework does not yet exist. In contrast, maturity is characterized by a smooth interaction between research and practice: a vocabulary has evolved, a general framework exists, and the capabilities and limitations of the area are widely appreciated. Virtually all practitioners have received exposure to the subject and are accustomed to recognizing the kinds of situations in which the method is applicable and even to articulating their problems in the language of the area, and most research is being conducted in response to obvious needs of practice.
>
> In between these two stages there is room for the uneven levels of development that characterize adolescence. New practice-generated problems for research are being identified, not only by growing numbers of experienced researchers, but also by the engineers in practice who have begun to appreciate which of their old problems the new area can help. These initial reactions from practice are often poorly articulated and often, unfortunately, too optimistic. Nonetheless one can see the establishment of certain consensus positions that determine both a framework and a viable set of solutions for at least some rather broadly defined problem areas. However, the development and internal

coordination of the area are still largely incomplete at this stage: some topics are virtually untouched, limits of effectiveness of the parts or the whole are not well understood, some applications are rather naively formulated, and some practical applications have begun to address a larger framework, but not yet with the confidence or the wisdom of experience.

Given the current status of the field, it can be argued that fire safety engineering is a healthy adolescent. There is not yet a single, generally accepted framework for undertaking a performance-based approach to building fire safety analysis and design, despite the extensive list of approaches and guides from around the world. In addition, there is disagreement as to how performance should be defined, the addition of "people" into the equation increases the uncertainty of the system considerably, and fire safety is effectively non-testable (the "system" is only tested when there is a fire). Nonetheless, a review of a various approaches currently available indicates that a comprehensive framework is close at hand that, at a minimum, should address the following fundamental concerns [11,37]:

1. There is a need to consider the level(s) of tolerable risk (personal and societal).
2. There is a need for clear specification of, and agreement to, fire safety goals and objectives, and performance and design criteria.
3. There is a need to understand how fire initiates, develops and spreads.
4. There is a need to understand how various fire safety measures (active and passive), including fire department operations, can mitigate potential fire losses.
5. There is a need to understand how people react in a fire situation.
6. There is a need to have, and to apply credible data, tools and methodologies in the determination of the above factors.
7. There is a need to consider the financial impact of fire safety decisions.
8. There is a need to address uncertainties in the analysis and design process.

**1. Level(s) of Tolerable Risk**

Consensus does not yet exist on what levels of risk are tolerable, on how they should be quantified and expressed, or on how they should be addressed in performance-based fire safety design [59]. This is due in part to the fact that tolerable levels of risk are value issues that scientists and engineers should not be deciding alone [28,59,60]. Society, through participation in the development of regulations, legal actions, and client demands, sets the boundaries of acceptability. To date, most performance-based regulations couch risk acceptability in terms of broad objectives and functional statements (NKB levels 1 and 2), and leave decisions regarding who is at risk, from what, and at what levels, to design engineers. Unfortunately, this can lead to considerable variability in risk analyses and final design solutions. Questions arise as to what population group is the design based upon, what criteria are appropriate to evaluate safe conditions for this group, and how sure is one that the resulting design is suitable for the range of population groups expected in the building. To move forward, consensus is needed on what risks are of concern, who is at risk and how, what levels of risk are tolerable, how risk should be quantified and expressed, and how risk should be addressed in performance-based fire safety design [61]. Scientists and engineers should provide facts to support decisions in these areas, and obtain broader input from society to help set the ultimate limits. If this is not done, the fire safety engineering community could see itself faced with designing to levels of risk and performance unacceptable to society.

**2. Fire Safety Goals, Objectives and Performance (Design) Criteria**

Scientific consensus on the definition of performance and for design criteria also does not yet exist. As such, how can performance-based fire safety design be widely accepted? Is performance a function of the building, its systems, its occupants, or all of these factors? How does one select appropriate performance criteria, and what makes them appropriate? For smoke detector activation, a given optical density may seem suitable, and for sprinkler activation, an upper layer temperature may seem appropriate, but should there be a time component involved as well? What are appropriate criteria for occupant safety? Regulations and guides tend to shy away from the use of "failure" criteria, such as death, and instead tend toward avoidance of untenable conditions. This, however, leads to such questions as how is tenability defined and for what target population? The fire science and engineering community can play a significant role by developing a technical consensus on performance criteria for all aspects of fire safety engineering. To support shortcomings in the profession's knowledge, advice and input should be solicited from appropriate professionals, such as medical doctors or human behavior specialists. The resulting criteria can then be submitted to regulatory developers who can decide which criteria should be used in the regulations and how. The fire safety engineering community can then develop tools and methodologies that use these criteria in an appropriate manner.

**3. Fire Initiation, Development and Spread**

Although more fundamental research will always be useful, the knowledge base on fire initiation, growth, and development is currently sufficient to allow fire safety engineering to be used for a variety of specific applications. However, the movement to performance-based codes is encouraging the use of performance-based fire safety design on a broader basis. For widespread use of performance-based design in structural engineering, well-defined loads and resistances were required. In fire safety engineering, such well-defined fire design loads and resistances do not yet exist. Presently, engineers tend to characterize fire loads on an individual enclosure or building basis. This results in different fire loads being used in different buildings, and does not provide a uniform or predictable level of safety throughout individual classes of buildings. For performance-based fire safety design to enjoy the same success as performance-based structural engineering, an effort is required to develop design-basis fire loads that can be applied uniformly across regulated buildings. This cannot be done by selecting a single characteristic design fire, or even a set of design fires, but may require the fire impact to be disaggregated into component loads. For each component load, a definable resistance should exist, as well as methods to calculate the resistance. With definable loads and resistances, relationships can be developed such that the overall fire performance of a structure can be evaluated in terms of resistance to component loads: in much the same way as structural engineering is currently performed. Allowable loads could then be defined in building regulations, based on building use, occupant characteristics, or other risk factors. These loads would, by default, reflect various fire impacts (as the use of various fire scenarios tries to accomplish today), and provide uniform measures for consistent code applications. Although some work is being done in this area [62], the concept is young, and if deemed valuable, will require considerable effort to bring it to fruition.

### 4. Mitigation of Potential Fire Losses

Loss experience, testing and research have provided a wealth of understanding of how to mitigate potential fire losses. As with the preceding discussion, mitigation technologies exist in usable forms; however, to be effectively addressed in a performance-based system, the mitigation technologies need to be understood in terms of the applied loads. In many respects, the information required to craft the relationships between the loads and how the technologies provide resistance already exist, and will fall into place as the other parts of the overall framework are developed. Keys to successfully addressing this item relate back to defining performance, clearly defining performance criteria, and understanding the level of fire impact (risk) tolerable to society. Addressing system reliability as part of performance will be critical, and should be a key component of performance-based fire safety design.

### 5. Human Behavior and Reaction to Fire

Better understanding of how people react in fire situations will provide valuable information for determining who will be at risk, from what, and at what stage of a fire. Such information would then lead to better selection of human factors criteria for use in regulations and design, with appropriate uncertainty bounds, and lead to better analysis and design tools. As with the discussion above, the fire science and engineering community needs to reach out to other professions, and to society in general, for assistance in this area. An encouraging step in this direction was taken with the First International Symposium on Human Behaviour in Fire, and it is hoped the interdisciplinary dialog begun at that symposium will continue [63].

### 6. & 8. Data, Analytical Tools, Evaluation and Design Methodologies, and Uncertainty

Fire scientists can continue to contribute significantly to the development of credible data and engineering tools and methodologies for use in performance-based fire safety design. As discussed earlier in this paper, the discipline has already made great strides in this area. However, more than ever, there is a need to understand, quantify, and address the uncertainties and unknowns in the data, tools, and methodologies. Fire test data can and should be provided with uncertainty bands, and should come with information regarding the test conditions, the test room, the instrumentation, and how the data was collected and recorded. Guidance on this exists outside of this profession [64] and within [65]. Similarly, engineering tools, be they simple analytical equations or complex computerized models, should be made available with discussion of applications, limitations, and uncertainties [66,67]. More important, perhaps, the uncertainties and unknowns in the overall performance-based fire safety design process need to be clearly identified and addressed where found to be significant. If it is found that the critical factors in a performance-based fire safety analysis and design involve people more so than the combustion process, should not more effort be focused on human behavior modeling instead of combustion modeling? What are the dominant factors with which fire safety engineers should be most concerned, and how concerned should they be? Although some work has been carried out in the area of uncertainty [35,36,37,68], much more is required, and it is likely to be one of the dominant need areas in the attempt to attain a robust and widely-accepted performance-based fire safety design framework.

## 7. Economic Impact (Benefit-Cost) Analyses

Benefit-cost analyses need to be considered as part of the development of a performance-based fire safety framework as well. Although perhaps not as critical to the fire science community as focusing on performance criteria, there is a need for engineers to understand what benefits are provided at what cost, and to be able to articulate this to regulators, clients, and regulatory developers. Again, the biggest challenge may be to find a balance between fire safety risks and costs that is at a level tolerable to society.

On a final note, given the current state of development of performance-based fire safety engineering, one would hope that only truly qualified and ethical engineers were practicing the profession, and that resulting designs always erred on the side of safety from everyone's perspective. Unfortunately, this is not always the case. There are relatively few fire safety engineers and code officials with the background needed to undertake or to review and approve performance-based designs [69,70,71,72,73]. This is particularly distressing in light of the shortcomings in design guidance and engineering tools. Even when qualified fire safety engineers are engaged, the lack of guidance documents, widely-accepted criteria, and evaluation methods makes each project different. This can make it difficult to provide consistency between projects, and result in questions from the local authorities [74]. In short, more and continuing education and supporting documentation are urgently needed.

## SUMMARY

Performance-based fire safety engineering has recently emerged as "the" approach to building fire safety design. This has been made possible primarily by advances in fire science and engineering and the global movement to performance-based building codes. However, the discipline of fire safety engineering and the concept of performance-based fire safety engineering are still developing, and much is required before the discipline can be considered mature. This paper has outlined the evolution of performance-based fire safety design, the current situation, and thoughts for addressing current shortcomings. The discussion of the shortcomings is not meant to imply that performance-based fire safety design should be stopped, but rather, that fire safety engineers proceed cautiously, with an understanding of what is acceptable to society, and with recognition of the limitations in the current technologies. As more information is developed, and fire scientists and engineers continue to work together and with allied professionals, performance-based fire safety engineering will grow into a mature, stable, and widely accepted discipline.

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