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ASSESSMENT OF THE TECHNOLOGICAL REQUIREMENTS FOR THE REALIZATION OF PERFORMANCE-BASED FIRE SAFETY DESIGN IN THE UNITED STATES

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Notice

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Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States

Final Report

Prepared for the

Building and Fire Research Laboratory
National Institute of Standards and Technology
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Abstract

Performance-based fire safety design methods are being used or developed in many parts of the world. The bases of several of these methods are the many fire engineering tools and methods developed in the United States. Unfortunately, these tools and methodologies are not being widely applied within the United States. There are many reasons for this, including the lack of performance-based fire and building codes in general use, and, where there are such codes or regulations, the lack of documentation on the availability and application of credible fire protection engineering tools and methodologies for fire safety design. To help assess the technological requirements for realization of performance-based fire safety design in the United States, the Society of Fire Protection Engineers, under a grant from the National Institute of Standards and Technology, Building and Fire Research Laboratory, conducted a research effort during the period September 1995 through August 1998. During Phase I of this effort, the intent of a performance-based approach to fire safety analysis and design was identified, performance-based approaches to fire safety analysis and design from around the world were identified and evaluated for applicability in the United States, and a framework for a performance-based approach to fire safety analysis and design for use in the United States was outlined. During Phase II of this effort, a focus group was convened to discuss concepts of a performance-based building regulatory system for the United States, including the role of engineering tools and methodologies in a performance-based system, and support was provided for the evaluation of engineering tools and for the development of engineering practice documents. During Phase III of this effort, the development of an engineering guide on performance-based fire protection analysis and design was begun, continued support was provided for the evaluation of engineering tools and for the development of engineering practice documents, and issues related to risk and uncertainty in a performance-based fire safety design environment were investigated. This report summarizes the activities of this three-year effort, and outlines future efforts required for widespread realization of performance-based fire safety design in the United States.

Acknowledgments

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Table of Contents

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Background and Introduction

Impetus for Research

When signed into law on 26 October 1992, the *Federal Fire Safety Act of 1992*[1] (the Act) became, in essence, the first performance-based fire safety code in the United States. This happened by virtue of allowing *either* the installation of automatic sprinklers *or* the installation of alternative fire protection measures that could be shown to provide *an equivalent level of safety* to that which the sprinklers would be expected to provide.*

The wording that allows for *an equivalent level of safety* to automatic sprinkler protection is what makes the Act a performance-based document. Instead of prescribing a list of fire safety measures that must be installed, it defines a level of performance that must be met by the recommended fire safety measures. It is one of the most important, yet most difficult parts of the law for many people to deal with. It is important because it recognizes that although sprinklers can provide a significant level of fire and life safety when properly designed and installed, there are other fire safety measures, that when properly designed and installed, can provide an equivalent level of safety for building occupants without the need for sprinklers. This provides a clear opportunity for undertaking a cost-benefit approach that can result in achieving a desired level of safety performance while realizing an economic benefit as well.

Unfortunately, *the use of performance concepts is new for many engineers practicing in the field of fire safety.* As a result, the flexibility and benefits provided in performance oriented codes are not being realized to their full potential. A primary reason for this is the way in which the majority of the members of the fire protection community currently do business: fire safety measures are designed and approved based upon a set of prescribed requirements and are often not engineered based on the specific fire safety needs and objectives of the client. As a result, when faced with a client objective, e.g., "provide a level of safety equivalent to a sprinklered building," *many engineers have difficulty translating this into engineering terms upon which to base a design.*

This is not to say that equivalency options do not exist and engineering of building fire safety is not performed. However, some of the approaches for determining equivalencies currently used in the United States provide a limited set of options based on prescribed equivalency parameters and do not require the solution to be "engineered."[2] In addition, the solutions are often founded more on expert opinion than on scientific principles, engineering analysis, or research data. Although such "packaged" approaches make the design and approval process for equivalencies very straightforward, they can also impose more limits on a design than necessary, and may not completely consider the performance of the building in a fire situation. Furthermore, *although many useful tools are available in the form of quantitative calculation methods, for use should an engineered approach be undertaken, there is a lack of published guidance documents as to what tools should be used, under what circumstances, and with what limitations* (boundary conditions). The absence of such guidance documents does little to boost the confidence of approval authorities during the design review process.

* The model building codes allow performance-based options via equivalencies, but "equivalent" is not defined.

Strategy for Addressing the Issues

In order to realize the full potential of innovative, safe, cost-effective, and sustainable buildings made available through the application of performance-based analysis and design concepts within a performance-based regulatory structure, it was realized that the underlying concepts need to become better integrated into the everyday practices of the building and fire communities. In addition, the design and analysis tools must become readily available, the performance-based regulations and supporting legislation need to be developed and implemented, and the required support and enforcement infrastructure needs to be established.

To achieve these goals in a manageable way, five fundamental areas have been identified in which to focus efforts: technology assessment, technology development, education, public policy research, and regulatory infrastructure support.

- Technology Assessment is required to determine what technology is currently available, whether or not it adequately meets the needs of the design, construction, and enforcement communities, and where additional research and development efforts can be directed in order to fulfill the technological requirements for performance-based codes.
- Technology Development is necessary to undertake and oversee research and development projects, and to integrate the research and development results into everyday use.
- Education is required for the transfer of knowledge to all the members of the building and fire communities who will apply, approve, or be affected by performance-based codes and design methods.
- Public Policy Research is required to support the development and availability of decision making tools that are needed, among other reasons, to address the perception of how safe buildings will be (e.g., from fire, natural hazards, and structural failure) under a performance-based regulatory system.
- Regulatory Infrastructure Support is necessary to identify and develop the regulatory and legislative instruments needed for adoption of a performance-based regulatory system, and to identify and develop the support and enforcement tools and methods needed for a performance-based regulatory system.

To begin addressing these issues, a proposal was submitted to the National Institute of Standards and Technology, Building and Fire Research Laboratory. The focus of the proposal was on the Technology Assessment area, with some efforts in the Technology Development area.

Research Plan for Technology Assessment and Development Effort

The primary objectives of this research effort were *to assess the availability and applicability of fire protection engineering tools and design methodologies for use within a performance-based approach to building fire safety design, and to identify gaps where additional research and development are needed.* Not only did this require assessment of available technology, but of the engineering approach within which the technology is used. In addition, it was deemed necessary to look at the overall regulatory structure needed to support widespread use and acceptance of performance-based fire safety design.

To achieve this objective, the effort was divided into four primary, yet over-lapping tasks.

1. Inventory and Review Existing Performance-Based Approaches to Fire Safety Design

As the concept of a performance-based approach to fire safety design was just emerging in the United States when this effort began, relatively few engineers had experience in the application of this type of approach to fire safety design. As a result, one of the first tasks was to determine what is meant by "a performance-based approach" to fire safety design as it relates to the fire protection community in the United States. This included review of performance-based design in other disciplines, and selection of a definition to describe a performance-based fire safety approach. Once the concept of performance-based fire safety design was defined, the next task was to identify and inventory the efforts related to performance-based fire safety design approaches world wide, and evaluate their applicability for use in the United States. The intent here was to avoid "re-inventing the wheel" and to take advantage of international experience.

2. Develop a Framework for Performance-Based Fire Safety Design for the United States

The next major task was to develop a framework for performance-based fire safety design for the United States. However, in addition to simply basing such a framework on the various performance-based fire safety design approaches in use or under development world wide, it was necessary to gain an understanding of how the broader building and fire communities felt about the use of such an approach in the United States. This was accomplished by convening a focus group on concepts of a performance-based building regulatory system for the United States. As part of the focus group discussions, terminology and definitions were developed to help describe a performance-based approach. Working from the consensus of the focus group and from the review of performance-based fire safety design approaches from around the world, a framework for a performance-based fire safety design approach for use in the United States was developed.

3. Identify and Evaluate Fire Protection Engineering Design Tools and Provide Guidance on Their Applicability and Limitations

Although there are a number of fire protection engineering design tools currently available, there is a certain degree of hesitancy in the application of these tools both to fire safety designs and to the review of designs in which these tools are applied. The primary reason for hesitation seems to be the lack of "accreditation" of the various tools by a neutral and expert forum. Such a "third-party" review by some one or some group aside from the person or group that developed the tool provides a significant "level of comfort" for both the design engineer and design reviewer. Similarly, although there are handbooks and other reference sources that provide a variety of specific engineering methodologies, these resources sometimes lack guidance on how to select an appropriate methodology for a specific problem, and often do not thoroughly discuss the limitations of the various methodologies presented.

4. Review Issues of Risk, Uncertainty and Decision-Making in Performance-Based Fire Safety

Concepts such as "equivalent level of safety" and "acceptable level of risk" are inherent in a performance-based system, and yet difficult for an engineer to address. In some cases, it may not be appropriate for an engineer to determine what is "acceptable," especially if it is a societal value issue. In addition, innovative engineering tools come with inherent uncertainties, and it is important for the practitioner to be able to identify and address them.

Research Activities and Outcomes

The following sections describe the outcomes of this three year research effort. In summary, a framework for performance-based fire safety design in the United States was developed, the evaluation of engineering tools for use within such a framework has been initiated, the development of engineering guidance documents for use within a performance-based building regulatory system has begun, and issues of risk, uncertainty, and decision-making in the performance-based fire safety design process have begun to be studied. In addition to the findings discussed in this report, reference is made to the following reports which contain additional information relative to the first two tasks outlined above: *The Evolution of Performance-Based Codes and Fire Safety Design Methods*,[3] and *Concepts of a Performance-Based Building Regulatory System for the United States*.[4]

1.0 Identification and Review of Performance-Based Design Methods

The first task of this effort required identifying what is meant by performance-based fire safety design and identifying the components of a framework for undertaking performance-based fire safety analyses and designs. This was accomplished by identifying, in general, what performance-based design means, developing a definition for performance-based fire safety design, researching developments in the area of performance-based fire safety design, and outlining a framework for a performance-based approach to fire safety analysis and design.

1.1 What is Performance-Based Design?

Performance-based design is a process of engineering a solution to meet specific levels of performance, often stated in terms of performance levels (or objectives) and performance criteria. In structural engineering, for example, the performance levels are often defined in terms of specific limiting damage states against which a structure's performance can be objectively measured.[5] This concept has guided structural engineers for years, especially with regard to design for dead, live, and wind loads. In recent years, the concept has expanded into the realm of design against unacceptable loss due to earthquake loads as well. In fact, the Structural Engineers Association of California (SEAOC) Vision 2000 project, initiated to provide engineers with a framework for performance-based engineering of buildings against earthquake loads, has defined performance-based engineering as "selection of design criteria, appropriate structural systems, layout, proportioning, and detailing for a structure and its nonstructural components and contents and the assurance of construction quality control such that at specified levels of ground motion and with defined levels of reliability, the structure will not be damaged beyond certain limit states."[5] Although this definition is more detailed than the previous one, the concepts are the same: performance-based design means designing to a specified and measurable level of performance.

1.2 What is Performance-Based Fire Safety Design?

Following the concept introduced above, performance-based fire safety design is a process of engineering a fire safety solution to meet a specific level of performance. In recent years, this concept has emerged, in some jurisdictions, as an acceptable means of undertaking fire safety analysis and design in the United States. However, a relatively small percentage of engineers working in the building and fire communities have experience in the application of performance-based approaches to fire safety design. In addition, there are discrepancies in the terminology and definitions used by design professionals, codes- and standards-making organizations, and Authorities Having Jurisdiction that cause unnecessary complications for those applying and reviewing performance oriented approaches to fire safety problems.

To address these fundamental concerns, the first task of this effort was to determine what is meant by "a performance-based approach" to fire safety design and how it relates to the fire protection community in the United States. This was accomplished by identifying and reviewing performance-based fire safety analysis and design approaches in use or under development around the world, by convening a focus group to discuss concepts of performance-based codes and performance-based fire safety analysis and design as they pertain to the United States, and proposing, in peer-reviewed publications, a framework for undertaking performance-based fire safety analysis and design. The results of these efforts are described below.

1.3 Existing Performance-Based Fire Safety Analysis and Design Methods

The first step towards identifying what is meant by performance-based fire safety analysis and design was to research the topic. As a starting point, the definition of performance-based fire protection engineering used in the SFPE short-course "An Introduction to Performance-Based Design for Fire Protection Engineers" was adopted:[6]

> *An engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives.*

With the above definition as a starting point, research was conducted into the evolution of performance-based codes and performance-based fire safety analysis and design approaches. This research effort resulted in the identification of more than a dozen performance-based fire safety analysis and design approaches under development or in use around the world. These include:

- *FiRECAM* (NRC, Canada)
- *FRAMEworks* (NFPRF, USA)
- *Building Fire Safety Evaluation Method* (Fitzgerald, WPI, USA)
- *Fire Engineering Guidelines* (FCRC, Australia)
- *The Application of Fire Performance Concepts to Design Objectives* (ISO)
- Draft for Development on the *Application of Fire Safety Engineering Principles to Building Fire Safety Design* (BSI, UK)
- *Performance Requirements for Fire Safety* and *Technical Guide for Verification by Calculation*, (Nordic Committee on Building Regulations, NKB, Fire Safety Committee)
- *Fire-Induced Vulnerability Evaluation (FIVE) Methodology* (EPRI, USA)
- *Fire Engineering Design Guide* (University of Canterbury, New Zealand)
- *Total Fire Safety Design System for Buildings* (MOC, Japan)
- *Fire Safety Evaluation System* (NFPA, USA)

A brief discussion of these approaches has been compiled and published in, "The Evolution of Performance-Based Codes and Fire Safety Design Methods."[3]

Despite the presence of this extensive list of analysis and design approaches from around the world, there is not yet a single, generally accepted framework within the fire and building communities for undertaking a performance-based approach to building fire safety analysis and design (although the ISO effort will likely result in a widely available methodology). This lack of a widely-available and generally acceptable methodology is due to a number of factors, including the complexity or simplicity of the available methodologies, the lack of data (probabilistic and deterministic), the lack of credible fire safety analysis and design tools, and in some cases, the relationship of a methodology to a specific regulation (e.g., the limitation in use of *NFPA 101A, Fire Safety Evaluation System,* as an equivalent method for compliance with the *NFPA 101, Life Safety Code®*).

However, a review of the above approaches indicates that, at a minimum, the following fundamental concerns should be considered when undertaking 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 of, and agreement to, fire safety goals and objectives, and performance and 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.
- There is a need to address uncertainties in the analysis and design process.

1.4 Summary

Given the presence of these common goals from around the world, it was concluded that it should be possible to develop a framework for performance-based fire safety analysis and design that is universally useable and acceptable. It was also concluded that these same goals support the definition for performance-based fire protection engineering adopted at the outset of the research effort: an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives. Furthermore, the need to address issues of risk and uncertainty were indicated as areas that need further research and development efforts.

To further test the above conclusions, specifically with regard to application of performance-based fire protection engineering (analysis and design) approaches in the United States, the following steps were taken:

- The SFPE convened a focus group of representatives from the building and fire communities to discuss concepts, terminology and definitions for a building regulatory system for the United States that includes the use of performance-based design approaches.[4,7]
- The concept of performance-based fire safety analysis and design, as taught in the SFPE short-course,[6] was submitted to and published in a peer-reviewed journal.[8]
- An SFPE Engineering Task Group was established to undertake a more in depth review of various performance-based fire safety analysis and design approaches from around the world and to develop an engineering guide on performance-based fire safety analysis and design.

2.0 Develop a Framework for Performance-Based Fire Safety Design for the United States

Given the definition of performance-based fire protection engineering and the concepts of a performance-based approach to fire safety design that were developed in the initial task of this effort, the next task was to develop a framework for performance-based fire safety design for the United States. This was accomplished by drawing on the information gained in the initial task, complemented by input received from a broad cross section of the building and fire communities in the United States.

2.1 Focus Group on Concepts of a Performance-Based System for the United States

To help the SFPE gain insight as to how the building and fire communities in the United States viewed the potential structure of a performance-based regulatory system, and to help the SFPE place the engineering aspects of such a system into perspective, the SFPE convened the *SFPE Focus Group on Concepts of a Performance-Based System for the United States* (hereafter referred to as "the focus group" or "the group") in March 1996.

The intent of the focus group was to obtain input from a wide cross-section of the United States' building and fire communities on the movement towards greater use of performance-based codes, standards and fire protection engineering and design methods in the United States. The goal to obtain input from a wide cross-section of the building and fire communities was achieved, with representatives of the following organizations participating in the effort:

- American Institute of Architects (AIA)
- American Forest and Paper Association (AFPA)
- American Hotel and Motel Association, Safety & Fire Protection Committee (AHMA)
- American Society of Civil Engineers (ASCE)
- American Society of Heating, Refrigerating & Air-Conditioning Engineers (ASHRAE)
- American Society of Testing and Materials (ASTM)
- American Wood Council (AWC)
- Building Officials & Code Administrators International (BOCA)
- Building Owners and Managers Association (BOMA)
- Council of American Building Officials (CABO)
- Factory Mutual (FM)
- Fire Marshals Association of North America (FMANA)
- Gage Babcock Associates (GBA)
- Hughes Associates Inc. (HAI)
- Industrial Risk Insurers (IRI)
- Insurance Services Office (ISO)
- International Association of Fire Chiefs (IAFC)
- International Code Council (ICC)
- International Conference of Building Officials (ICBO)
- ITT Sheraton Corporation
- National Association of State Fire Marshals (NASFM)
- National Fire Protection Association (NFPA)

- National Fire Sprinkler Association (NFSA)
- National Institute of Standards and Technology (NIST)
- Performance Advisory Group (PAG)
- Portland Cement Association (PCA)
- Professional Loss Control (PLC)
- RJA
- Society of Fire Protection Engineers (SFPE)
- Southern Building Code Congress International (SBCCI)
- Underwriters Laboratories Inc. (UL)
- University of Maryland, Fire Protection Engineering Department(UM)
- United States Department of Energy (DOE)
- United States Fire Administration (USFA)
- United States General Services Administration (GSA)
- United States Nuclear Regulatory Commission (NRC)
- Wisconsin Electric Power Company (WEPCO)
- Worcester Polytechnic Institute, Center for Firesafety Studies (WPI)

In addition, representatives from a number of international organizations, actively involved in the development, application or enforcement of performance-based regulations or fire safety design methods in their countries, participated as well:

- Arup Fire, UK
- Australian Building Codes Board, Australia (ABCB)
- Building Industry Authority, New Zealand (BIA)
- International Council on Building Research Studies and Documentation, the Netherlands, (CIB)
- Department of the Environment, UK (DoE)
- Fire Code Reform Centre Limited, Australia (FCRC)
- Fire Research Station, UK (FRS)
- Fire Risk Consultants, New Zealand
- Glasgow Caledonia University, Scotland
- Loss Prevention Council, UK (LPC)
- National Research Council, Canada (NRCC)
- The Home Office, UK

To initiate discussion, participants in the group were given background materials, a working concept for a performance-based system (a three-component system including a code, engineering standards and practices, and evaluation tools and methods), and suggested definitions as bases. They were then asked to comment on the materials provided and to attend meetings to discuss the materials.

The primary objectives for 1996 were to discuss and gain consensus on five key issues:

1. Why does there appear to be such a strong movement towards performance-based codes in the United States?
2. Do we need a performance-based regulatory system for the United States, and what might it entail?

3. What might the components of such a system be?
4. How might the components be developed, formatted, implemented and enforced?
5. What needs to be accomplished before widespread implementation and acceptance of such a system can occur?

2.1.1 Focus Group Consensus

To discuss the above issues, the SFPE Focus Group on Concepts of a Performance-Based System for the United States convened two meetings during 1996: 25-26 April at the Doubletree Hotel in Arlington, VA, and 23 September at the Sheraton Ottawa Hotel in Ottawa, Ontario, Canada. Over the course of the two meetings, the following consensus was reached:

- The United States needs to pursue a performance-based building regulatory system.
- A performance-based system for the United States will likely spawn from the present system, will include explicit policy level goals, functional objectives and performance requirements in the codes (to describe the level of safety that is desired), and will utilize both prescriptive solutions (as we currently have) and performance-based solutions as acceptable means to provide the desired level of safety.
- An initial step in the transition to a performance-based system will be to extract goals and objectives from the current codes (to be primarily accomplished by the codes- and standards-making organizations) and to quantify them.
- Policy level goals must be developed by all interested parties.
- Tools and techniques to measure performance must be developed (the responsibility of many professionals, including the SFPE).
- An engineering guide for developing performance-based solutions needs to be developed (a task the SFPE has initiated).
- A common vocabulary and acceptable definitions need to be developed.
- The overall level of education needs to be raised for everyone in the building and fire communities, especially on performance-based code and design method issues.
- A short-term education goal is to determine what the current code requirements are (in terms of intent and objectives) and to explain why they are required.
- Another short-term education goal is to provide information on the basics and the conceptual background related to performance-based codes and fire safety design methods.
- A long-term educational goal is to provide applications-oriented education to all practitioners.
- Building and fire professionals, especially engineers, need a higher level of qualifications, a higher standard of ethics, and more accountability for a performance-based system to work.
- Good design documentation is mandatory for a performance-based system to work.
- The SFPE should be the facilitator in: a) defining the core competency requirements for those engaged in performance-based fire protection engineering and for those working with performance-based regulations, and, b) building relationships among allied professionals to validate competency (e.g., other engineering disciplines, building officials, architects, etc.).
- The SFPE needs to transmit the information to practitioners that their involvement is critical to the successful implementation of a performance-based system: they will make the difference.

- The SFPE needs to archive knowledge for a performance-based system, such as has been begun with the *SFPE Handbook of Fire Protection Engineering.*
- More outreach is needed to allied professionals to deliver the message of a systems approach to building (fire safety) design.
- Resources are needed for the SFPE and others to deliver on the above items.

2.1.2 Summary

Consensus on the concepts for a performance-based building regulatory system for the United States has given the United States' building and fire communities a solid platform from which to build. To date, the focus group consensus has played a role in the ICC Performance Committee's effort to develop a performance-based building code, in the development of educational publications and presentations on performance-based concepts, and in outlining technological requirements for the realization of performance-based fire protection engineering in the United States. A key technological requirement is the development of a guideline, or a framework, for undertaking performance-based fire safety designs. (A detailed report of the 1996 activities of the focus group has been published as a NIST GCR.[3] The same report, with the addition of written comments from the focus group participants, is available from the SFPE.[7])

2.2 Framework for a Performance-Based Fire Safety Design Guide for the United States

With input from the United States' building and fire communities on the need for a design guide to support performance-based fire safety design, and with the review of fire engineering design guides from around the world, work has begun on a design guide for the United States. The starting point for development of the guide is the definition of performance-based fire safety design stated previously: an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives.[†]

When one takes this definition and views performance-based fire safety design as an engineering process, one finds that the process can be divided into seven fundamental steps:[8]

1. Identification of site or project information,
2. Identification of fire safety goals and objectives,
3. Development and selection of performance criteria,
4. Development of fire scenarios, design fire scenarios and design fires,
5. Development of candidate design options,
6. Evaluation of candidate design options and selection of a final design, and
7. Development of final design documentation.

These seven steps, which are found in one form or another in most fire protection engineering guidelines in use or under development around the world,[3] encompass the fundamental aspects deemed necessary for a performance-based fire safety analysis and design approach. As such, they can serve as a solid foundation for development of a framework for performance-based fire safety analysis and design for the United States.

The basic flow of the above steps are outlined in Figures 1 and 2. In Figure 1, the process is outlined as a sequential process from Step 1 through Step 7. In reality, however, there will be several iterations, especially during the evaluation stage (Step 6). The iterative nature of the evaluation, including the possibility of revisiting selection of performance criteria is illustrated in Figure 2.

[†] An alternate definition that resulted from the focus group discussion defines performance-based fire safety design as an engineering approach to fire safety design based on: (1) agreed upon fire safety goals and objectives, (2) deterministic and probabilistic evaluation of fire scenarios, and (3) a quantitative assessment of design alternatives against the fire safety goals and objectives. Although different wording is used, the two definitions are essentially the same.

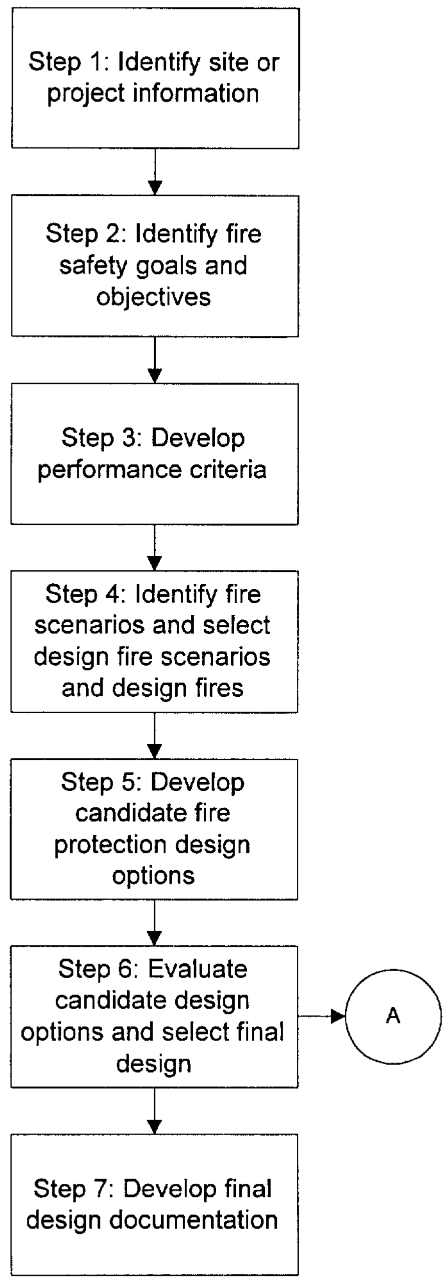

Figure 1. Flowchart of the Seven Steps in a Performance-Based Fire Protection Design Process

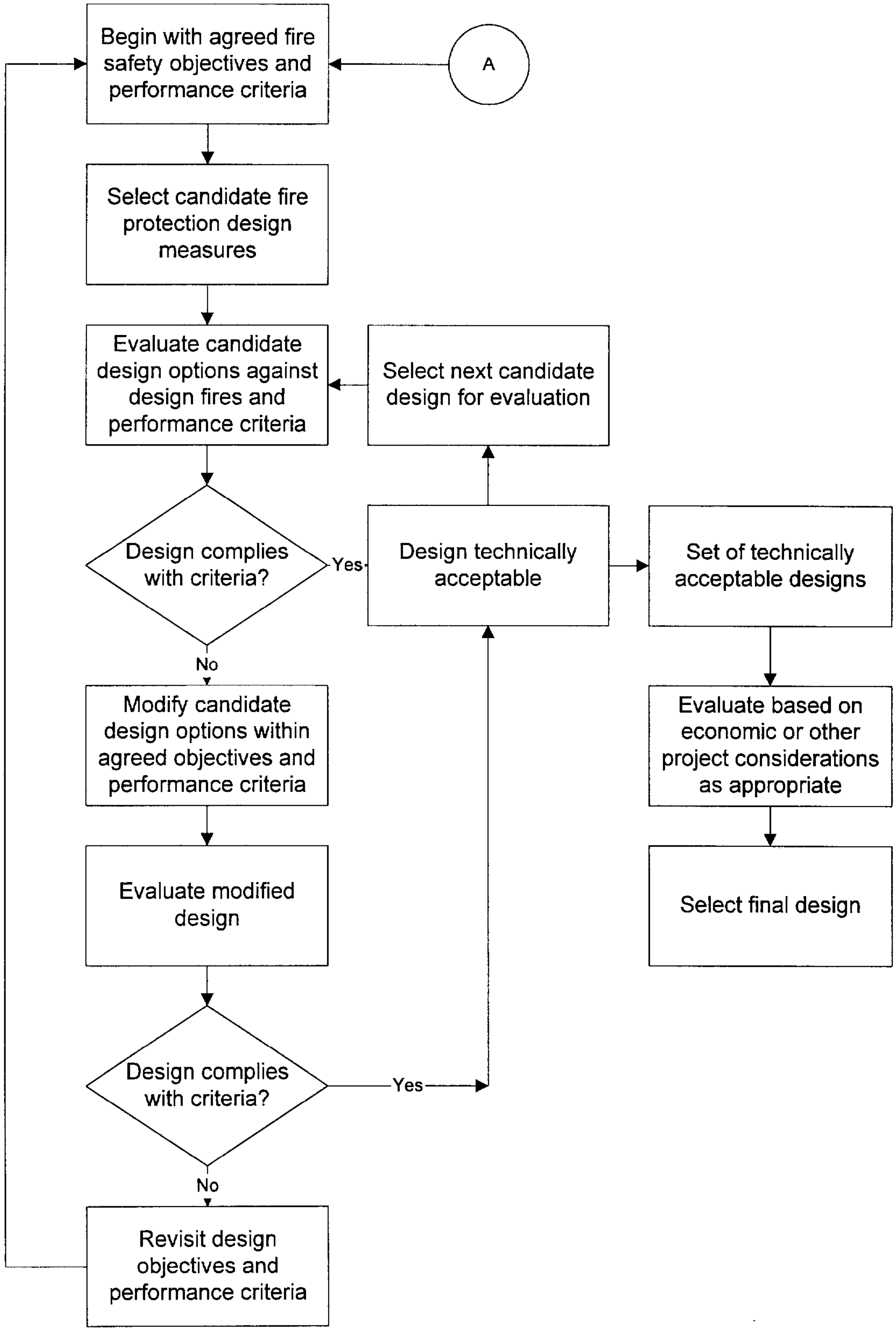

Figure 2: Iterative Nature of the Performance-Based Design Evaluation Process

2.2.1 Step 1: Identify Site or Project Information

The first step in the process is to gather information about the site, structure, facility or process. This includes building characteristics, such as size, layout, use, and construction, with particular attention paid to special features such as high-ceiling and large volume spaces (e.g., atria or warehouses), or where high occupant loading might be expected (e.g., malls, auditoriums and stadiums). Operational characteristics relate to specific functions of the building or process, or to needs of the business itself. This category includes such items as the presence of special or unique processes, hazardous material use or storage, areas of high value equipment, and areas where down-time needs to be effectively zero, such as in a semiconductor clean room. Finally, it is important to characterize the occupants. This characterization will vary by use of the building (e.g., residential versus business), and should include such factors as ages, abilities, whether people sleep in the building, and whether the occupants can be considered as individuals that can make their own decisions or as members of groups relying on a decision maker (e.g., families with small children, school children, patients in hospitals).

2.2.2 Step 2: Identify Fire Safety Goals and Objectives

In general, *goals* are non-controversial statements that reflect a common aim. They are often easy to agree with and are measured qualitatively, if measured at all. In the area of fire safety, there are four fundamental goals that fit this definition: protection of life, protection of property, protection of mission (continuity of operations), and protection of the environment from the unwanted affects of fire and fire control. In the fire safety design area, one normally sees a fire safety goal expressed as a broad statement that reflects the stakeholders' expectation of the level of fire safety desired. This same definition is valid from a code perspective, where the phrase "stakeholders' expectation" may be replaced with the term "public's expectation."

As an example of how a fire safety goal might appear in a code, consider the following example from the 1994 NFPA Life Safety Code®: "Protect the occupants not intimate with the initial fire development from loss of life."[9] Similarly, a business owner's goal related to protection of mission might be to "protect my business from operational losses due to the damaging effects of fire." These are statements that everyone agrees with. However, everyone may not agree how best to meet them. This is where objectives play a critical role.

Objectives are used to provide more direction as to how a goal might be met, and are normally stated in quantifiable terms. In performance-based design, one could find an objective expressed as a *stakeholder objective* or as a *client loss objective* (some indication of the level of loss that the client can tolerate). An example of this might be to "protect the piece of equipment in Room X against the effects of fire such that a return to full operation can occur within 24 hours." Here, in order to meet the goal of maintaining continuity of operations, the objective is to ensure that the equipment is not out of service for more than 24 hours.

In a performance-based code, one might see a *functional objective* that describes how a building or its systems will meet a fire safety goal. An example might be to "give people not intimate with the initial fire development adequate time to reach a safe place without being overcome by the effects of fire." In essence, this says that the building and its systems must function in such a way as to enable people to escape to a safe place in the event of a fire in order to meet the goal of life safety.

Once the stakeholder objectives or functional objectives are clearly defined and agreed to by those involved in the design process, one must have a means of identifying the level at which the building and its systems should perform in order to meet these objectives. This is done through statements called *design objectives* (in performance-based design) or *performance requirements* (in performance-based codes). For example, a design objective for mission protection might be: "limit the deposition of corrosive products of combustion to less than those quantities that would cause irreversible or unrecoverable damage." In this case, if one knows the limit of product deposition that will cause the damage, and can calculate the species production and deposition rate, one can design to meet this requirement.

In performance-based codes, one typically finds *performance requirements*, which are statements of the level of performance that must be met by building materials, assemblies, systems, components, and construction methods in order for the fire safety goals and objectives to be met. Not only should one be able to quantify these parameters, one should be able to measure or calculate them as well. For example, one might see performance requirements such as, "limit the spread of fire to the room of origin, alert the occupants prior to smoke spread beyond the room of origin, and maintain tenable conditions in the paths of egress until the occupants reach a safe place" in performance-based codes. Each of these requirements relates to how the building and its systems should perform in meeting a specific life safety goal and functional objective, and they each can be measured or calculated.

2.2.3 Step 3: Develop Performance Criteria

Performance criteria are the metrics against which design objectives or performance requirements are assessed. Unlike design objectives or performance requirements, which are often stated qualitatively, performance criteria must be stated in such a manner that they can be directly measured or calculated (e.g., temperature, thermal radiation, and smoke layer depth), as these become the criteria on which a design will be based.

To help put all these different requirements and criteria into perspective, consider the following simplified example based on a goal of life safety.

- The *fire safety goal* is to protect those people not intimate with the first materials burning from loss of life. (This is easy to agree with, yet difficult to quantify.)
- To meet this goal, one *stakeholder objective* (or *functional objective*) might be to provide people with adequate time to reach a safe place without being overcome by the effects of fire. (This provides a little more detail: one could infer that protection must be provided against heat, thermal radiation, and smoke.)
- To meet this objective, one *design objective* (or *performance requirement*) might be to limit the fire spread to the room of origin. (If the fire does not leave the room, the people outside of the room of origin will not be exposed to thermal radiation or extreme temperature, and their exposure to smoke will be minimized.)
- To meet the performance requirement, an engineer might establish a set of *performance criteria,* such as a maximum upper layer temperature of 400°C and a maximum heat flux at floor level of 10 kW/m^2 in the room of fire origin. (These criteria have been selected to represent prevention of flashover in the room of fire origin. Prevention of flashover was selected because fire spread beyond the room of origin almost always occurs after flashover

when the upper layer gases ignite and spread along the fire front, so prevention of flashover means prevention of fire spread. In many cases, several design criteria will be needed to demonstrate that a performance requirement has been met.)

2.2.4 Step 4: Develop Fire Scenarios, Design Fire Scenarios, and Design Fires

A fire scenario is a description of a specific fire situation from ignition, through established burning, to the maximum extent of growth and resulting decay. There is, for the most part, an infinite number of fire scenarios possible for any given building. As this range of fire scenarios includes situations that may be considered highly unlikely, it is possible to pare the scenarios down into a smaller group of fire scenarios that will be used as part of the design process. These are called design fire scenarios. The range of design fire scenarios selected for consideration should reflect both probabilistic and deterministic considerations; that is, how likely is it that this fire will occur, and if it does occur, how is it expected to develop and spread.

There are many factors that one must consider when developing fire scenarios and paring them down into design fire scenarios, including:

Pre-fire situation: building, compartment, conditions.
Ignition sources: temperature, energy, time and area of contact with potential fuels.
Initial fuels: state, surface area to mass ratio, rate of heat release.
Secondary fuels: proximity to initial fuels, amount, distribution.
Extension potential: beyond compartment, structure, area (if outside).
Target locations: note target items or areas associated with client loss objectives along the expected route of spread for fire and fire effluents.
Occupant condition: alert, asleep, self-mobile, disabled, infant, elderly, etc.
Critical factors: ventilation (windows, doors), environmental, operational, etc.
Relevant statistical data.

Once a set of design fire scenarios has been developed, a set of corresponding design fires need to developed. A design fire is an engineering description of a specific fire scenario. Design fires are used to evaluate the candidate design options, much the same as a design loads will be used in structural design to ensure that the strength of a structure is adequate. Design fires may be characterized by parameters such as heat release rate, fire growth rate, species production, species production rate, or other fire related parameters that can be measured or calculated. The most common way of characterizing a design fire is through the use of a fire growth curve. Common characteristics of a fire growth curve include a growth period, peak heat release rate, steady burning period and decay. A curve such as this may be representative of a single item burning in a furniture or room calorimeter, and would need to be adjusted accordingly for use in a design problem, especially where additional items become ignited and contribute to the fire. Design fire curves such as this need to be developed for every fire scenario considered for a compartment, building, structure, or process.

2.2.5 Step 5: Develop of Candidate Designs Options (Design Alternatives)

After the design fire scenarios and design fire curves have been developed, the next step is to develop candidate designs options (design alternatives). Candidate designs should be selected from fire protection components, systems, and strategies that will ensure the design objectives are met. In most cases, a number of candidate design options should be considered, including the code-prescribed requirements. As one reviews the various fire engineering approaches from around the world,[3] one finds that each one of the approaches considers various fire protection "sub-systems," often under the following (or similar) headings:

- Fire initiation and development,
- Spread, control, and management of smoke,
- Fire detection,
- Fire suppression (including fire department response and suppression activities),
- Occupant behavior and egress, and
- Passive fire protection.

Most fire protection engineers are familiar with these sub-systems and work with them under different labels, often defined by the prescriptive codes or test methods in use. For example, fire initiation and development encompasses material control, fire prevention, fuel loading, and similar fire growth factors, while passive fire protection would encompass fire resistance of materials. Regardless of the label used to describe these sub-systems, each of them must be considered in any performance-based fire safety analysis and design approach to be used in the United States.

2.2.6 Step 6: Evaluate Candidate Designs Options and Select Final Design

After the candidate design options have been developed, the next step is to evaluate them for compliance with the design objectives and performance criteria, and select a suitable option as the final design. The evaluation process is an iterative one wherein a variety of fire safety measures are evaluated against the design fire curves and the design objectives. Factors such as the addition of smoke detectors or automatic sprinklers, modifications to the ventilation characteristics, and variations to construction materials, interior finish and contents are evaluated here. In many cases, code-prescribed requirements will serve as a baseline for evaluation and review, and it is important to know if the code requirements meet the performance criteria, exceed them, or fall short of them.

A useful technique in evaluating whether or not the performance criteria are being met is the concept of Q'_{do} and Q'_{crit}.[8] As was discussed earlier, a performance criterion is a metric against which a design will be assessed in its ability to meet a performance requirement (design objective). For example, in the case of a design fire of a specific heat release rate, Q', one performance criterion might be the maximum fire size that can be tolerated before a specific performance requirement (e.g., flashover in the room of origin) is exceeded. This "maximum tolerable fire size" can be characterized by a maximum heat release rate, indicated here as Q'_{do}, where the subscript "$_{do}$" denotes "design objective." There will be a value of Q'_{do} for each design objective in the project. Similarly, for each design objective, there will be a critical point at which detection must occur in order to initiate the actions that will limit the fire size to less that the design objective. This is indicated by the term Q'_{crit}.

To meet the goal of preventing flashover, for example, one candidate design might be the use of an automatic sprinkler system. To be effective, the sprinkler must activate and begin to control the fire growth prior to the room reaching flashover. In this case, the point of flashover would be

Q'_{do}, and the point at which sprinkler activation is required would be Q'_{crit}. If one assumes, as an example, that flashover will occur when the heat release rate reaches about 800 kW, that value becomes Q'_{do}, the design objective that should not be exceeded. If the activation of a sprinkler system is being contemplated as a means for preventing flashover, there will be some point prior to Q'_{do} at which the sprinkler head must sense the fire and activate: Q'_{crit}. Given that the fire will be growing, and that there will be delays due to heat transfer to the link, Q'_{crit} will have to be selected at some point prior to Q'_{do} in order to fulfill its expected function. If the value of Q'_{crit} is too close to the value of Q'_{do}, there may be insufficient time for the sprinkler to activate in order to meet the design objective, and the parameters of the design alternative will need to be adjusted. In this situation, that could mean a change in spacing, sprinkler RTI or even fuel loading in the room.

A time line is a useful tool in evaluating design alternatives and selecting appropriate values for Q'_{crit}. For example, assume the design objective, Q'_{do}, is defined as the heat release rate that corresponds to the point when untenable conditions are reached in a given area. In this case, tenability may be defined in terms of an upper layer temperature, radiant heat flux, carbon monoxide concentration, or similar limiting factors. (The limiting or threshold values for these become the performance criteria.) Once the design objective has been established, one can work backwards through the fire development, noting the times required for such factors as travel time, decision-making time, time to become aware of the fire, and detector and alarm system activation. By identifying the actions, and noting the time required for each action, one can estimate the time required between detection and meeting the design objective. If the analysis shows that there is insufficient time from detector activation until the occupants are expected to be safe, the design alternative must be modified or rejected. Again, this is an iterative process, and a number of design alternatives and modifications are likely before a final design can be selected.

```
         t_detection      t_alarm   t_aware    t_decision   t_travel   t_safety              t_untenable
|----------|---------------|----------|-----------|------------|----------|----------------------|---
t_0      t_crit (Q'_crit)                                                                 t_do (Q'_do)
                                                                         |----------------------|
                                                                               safety margin
```

The concept of establishing a Q'_{do} and a Q'_{crit} for each design fire is extremely useful. Although Q'_{do} will not change for any given design fire curve, the value of Q'_{crit} will vary with each design alternative. As such, it provides a useful tool for evaluating design alternatives. In addition, a graphical representation of Q'_{do} and Q'_{crit} can provide some insight into evaluating the sensitivity of the design alternative to the fire growth rate. If Q'_{crit} and Q'_{do} are close to each other, and they are both on the steep slope of the fire growth curve, it is an indication that there is little room for error in the selection of Q'_{crit}. In this case, Q'_{crit} can be adjusted to provide a factor of safety by increasing the time between Q'_{crit} and Q'_{do}.

In addition to the concept of establishing a Q'_{do} and a Q'_{crit} for each design fire, common tools for evaluation include computer fire models (deterministic evaluations) and risk analysis methods. Although how these tools are applied in the evaluation was beyond the scope of this task, subsequent tasks began to look at these issues (see Section 3 and Section 4 of this report).

2.2.7 Step 7: Developing Final Design Documentation

The final step in the process is documenting the analysis and design and preparing equipment and installation specifications. The analysis and design report will be a critical factor in gaining the acceptance of a performance-based design. It needs to outline all of the steps taken during the analysis and design, and present the results in a format and manner acceptable to the authorities and to the client (stakeholder).

At a minimum, the report should include:

Intent of the analysis or design: the reasons it was undertaken.
Statement of design approach (philosophy): the approach taken, why it was taken, what assumptions were made, and what engineering tools and methodologies were applied.
Site or project information: hazard analysis and description of the structure, process and/or occupants, e.g., hazards, risks, construction, materials, use, layout, existing systems, occupant characteristics, etc.
Statement of client goals and objectives: the agreed upon goals and objectives of the performance-based analysis or design, who agreed and when.
Performance criteria: the performance criteria and the performance requirements (design objectives) to which they relate, including any safety or reliability factors applied, and support for safety or reliability factors where necessary.
Design Fire scenarios: the design fire scenarios used, the bases for selecting and rejecting fire scenarios not used as design fire scenarios, and assumptions and design restrictions (conditions).
Design fire(s): the design fire(s) (design fire curves) used, the bases for selecting and rejecting design fire(s), and assumptions, limitations, and design restrictions (conditions).
Candidate designs: the design alternative(s) selected, bases for selecting and rejecting design alternative(s) (deterministic, probabilistic), assumptions, conditions, limitations and uncertainties. This should include comparison of results with the performance criteria and design objectives and a discussion of the sensitivity of the selected design alternative to changes in the building use, contents, occupants, etc. When used, this should step should also include the specific design objective value (Q'_{do}) and the critical fire size value (Q'_{crit}) selected.
Uncertainty factors: any uncertainty (safety, reliability) factors, how they were derived, and/or appropriate references.
Cost-benefit analyses: where cost is a factor in the decision-making process, cost-benefit analyses should be included as well.
Design tools and methods used: the engineering tools and methods used in the analysis or design, including appropriate references (literature, date, software version, etc.), assumptions, limitations, uncertainties, engineering judgments, input data, validation data or procedures, and sensitivity analyses.
Test, inspection and maintenance requirements: test procedures, maintenance schedules, etc.
Fire safety management concerns: discussion on changes in use, contents or materials, training and education for building staff and occupants, etc.
References: software documentation, journal reports, handbook references, technical data sheets, fire test results, etc.

With regard to both the design and the fire safety management aspects, it is important to consider the expected use of the building, throughout its lifetime, when designing the fire safety systems.

There should be clear indicators, in the design documentation, as to the limits of the design and to any specific factors that will warrant a re-evaluation or re-design. These may include change of occupancy, significant change of fuel loading, or significant modifications to the building or its systems.

Concerning equipment installation specifications, although one may undertake a performance-based analysis and design, at the end of the day, the installation of the equipment, systems and features will have to be specified in exactly the way it is done today. The analysis and design may consider a variety of features, and the resulting design may have modified sprinkler spacing, exit widths, or number of doors, but the installation specification will still indicate how many, what size, and where they go. In this regard, the future for installers and inspectors will not significantly change.

2.2.8 Economic concerns

A performance-based fire protection analysis and design approach would be incomplete if it did not consider some level of cost-benefit analysis. The SFPE Focus Group,[4] as well as others internationally,[3] have identified cost-savings as a critical factor in the transition from a prescriptive-based to a performance-based regulatory system. A principle argument is that money can be saved by minimizing the redundant fire safety measures, prescribed by current codes and standards, when a performance-based design is undertaken. It follows, then that a cost-benefit analysis will be required as part of the design justification. (A review of performance-based approaches from around the world indicates that this issue requires more attention.) This issue should be addressed as part of any performance-based fire safety analysis and design approach for the United States.

2.2.9 Risk, Uncertainty, and Decision-Making Issues

One of the key technological requirements for implementation of performance-based fire protection analysis and design is adequately addressing issues of risk, uncertainty, and decision-making under uncertainty. In general, there are risks associated with application of emerging fire protection engineering technology, as with any emerging technology, as all may not be known about the technology or its limits of application. This does not mean the technology should not be used, but rather, that the risks and associated uncertainty should be identified and addressed. In some cases, risk and uncertainty can be addressed by regulation. In other cases, specific analysis of uncertainty and use of uncertainty factors may be required. In all cases, identifying areas of risk and uncertainty, and more appropriately, those areas that require special attention, may be addressed during the process of deciding what the problem is, how it can be addressed, and what tools and methods are appropriate. These issues will be discussed in more detail in Section 4 of this report.

2.2.10 Transitioning the Framework into a Performance-Based Fire Protection Analysis and Design Guide

To assist in the evaluation of fire engineering guides from around the world, and to develop such a guide for the United States, the SFPE established the Engineering Task Group (ETG) on Performance-Based Fire Safety Analysis and Design in 1996. The focus of this group is to develop the fundamental process-and-procedure document (framework document) describing a methodology for undertaking (and reviewing) performance-based fire safety analysis and designs. The basis for this ETG's efforts is the framework for performance-based fire safety analysis and design described earlier in this section. The intent is to develop a document that will help design engineers and regulatory officials (Authorities Having Jurisdiction, AHJs) to understand the performance-based analysis and design process, to identify engineering tools and methodologies available for use within the process, and to apply the engineering tools and methodologies with confidence. The resultant document will likely be called the *SFPE Engineering Guide for Performance-Based Fire Protection Analysis and Design*, and will be published by the National Fire Protection Association.

The basis for the *SFPE Engineering Guide for Performance-Based Fire Protection Analysis and Design* (the guide) is the framework discussed in the preceding section. The goal for the SFPE ETG on Performance-Based Fire Safety Analysis and Design is to have the guide completed by August of 1999. A draft of the guide will be available from the SFPE in January 1999 for review and comment by all interested parties.

2.2.11 Summary

A framework for performance-based fire protection and analysis has been developed for the United States. The framework has been discussed with the building and fire communities, in the context of a performance-based building regulatory system, and acceptance of the concept has been indicated. The framework is currently being formalized into a design guide and is expected to be widely available by August 1999.

3.0 Evaluate of Fire Protection Engineering Tools and Provide Guidance on Their Use, Application, and Limitations

As stated in previously, one of the primary objectives of this research effort was to assess the availability and applicability of fire protection engineering tools and design methodologies for use within a performance-based approach to building fire safety design. Whereas the previous tasks established a framework for application of performance-based fire safety design concepts, this task focused on establishing mechanisms for evaluating fire protection engineering tools and methods, and for reporting on their uses, applications, and limitations. Within the resources available, this task was accomplished by supporting the establishment of three Engineering Task Groups (ETGs) within the Society of Fire Protection Engineers: the ETG on Computer Model Evaluation, the ETG on Engineering Practice Documents, and the ETG on Performance-Based Fire Safety Analysis and Design. In addition to supporting the establishment of the three SFPE ETGs, resources were allocated to students and faculty at the University of Canterbury (Christchurch, New Zealand), the University of Maryland (Maryland, USA), and the Worcester Polytechnic Institute (Massachusetts, USA) to support the ETG efforts.

3.1 SFPE Engineering Task Group on Computer Model Evaluation

Performance-based fire protection analysis and design often utilizes emerging engineering tools, such as computer fire models. Although this can be good from the perspective of advancing technology and the fire protection engineering profession, care must be used to ensure that tools are used properly: for appropriate applications, within the bounds of intended use, and with a good understanding of the limitations.

Although cautions such as the above have been previously published for computer fire models,[10] [11] some evaluations have occurred,[12] and guidelines for computer model evaluation exist,[13,14] there is currently no organization in the United States formally evaluating (validating, or verifying) computer fire models, issuing certifications or listings of any type, and providing guidance for practicing engineers (and building and fire authorities). As a result, many building and fire authorities voice concern about the reliability, accuracy, and appropriateness of the models used, the applicability of the input data applied, the validity of the assumptions made, and ultimately, of the appropriateness of the solution developed.[15]

These concerns have been recognized, and as stated in the previous section, it is understood that for performance-based fire protection design to be widely accepted in the United States, computer fire models with known degrees of accuracy and reliability are required, valid and applicable data are needed for use with those models, assumptions made as part of the modeling effort need to be clearly stated and supportable.[16,17,18] To begin addressing these concerns, the SFPE formed an Engineering Task Group (ETG) on Computer Model Evaluation, whose goal is to evaluate the stated applications, limitations, and uses of computer fire models.[19, 20]

The purpose of this ETG is to produce evaluation reports on computer models to assist both the users of the models and the reviewers of analyses and designs based on models in gaining a better understanding of the intended use of a particular model, its evaluated range of application, and its known limitations. To minimize duplication of effort, the ETG on Computer Model Evaluation utilizes various American Society of Testing and Materials (ASTM) guides, i.e., ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Fire Models,[14] ASTM E 1472, Standard Guide for Documenting Computer Software for Fire Models,[21] and ASTM E 1591, Standard Guide for Data for Fire Models.[22] Additional evaluation criteria and procedures have been used and/or developed as necessary.

The first model selected for evaluation was DETACT-QS, a heat and smoke detector activation model. This model was selected as the first model for evaluation due to its simplicity, its limited scope of intended use and application, and its widespread usage by practicing engineers. A full report on this evaluation will soon be available from the SFPE.[20] To undertake the evaluation of DETACT-QS, a number of sub-groups were established, including Data for Evaluation and Algorithm Evaluation. Part of the evaluation was intended to compare the model with the original test data on which the main algorithm was based. In addition, fire test data were needed to evaluate the model's predictive capabilities. The first problem encountered was that the original test data, upon which the model's basic algorithm had been based, was no longer available. This meant evaluation of the algorithm would be problematic. Second, to evaluate the breadth of the model's applicability, test data were required under various compartment configurations. Although a large collection of fire test data exists, most fire tests did not document the information required for comparison with computer fire models. Third, for that data which did exist, little to no information was provided on the uncertainty or variability in the test data: an important factor if used as input data to a model.[13]

Given the lack of data in the required form, funding under this grant was allocated for a number of large scale fire tests to be performed at Underwriters Laboratories Inc., for the purpose of obtaining fire data for comparison with the model DETACT-QS. The intent was to perform a series of fire tests, a) to evaluate uncertainty and variability due to test methods and measurements, b) to evaluate the uncertainty in the algorithms used in the models, and c) to begin the compilation of a data base for fire test data for use in computer fire model evaluations, for use as input data for computer fire models, and for general analysis. Findings relative to the variability and uncertainty in the test data, to the uncertainty in the algorithm, and to the agreement between the test data and the model are included as part of the DETACT-QS evaluation report.[20]

3.2 SFPE Engineering Task Group on Engineering Practice Documents

As discussed previously, a performance-based building regulatory system will require engineering practice documents and guides (see discussion of the focus group). To begin addressing this need, the SFPE established an Engineering Task Group (ETG) on Engineering Practice Documents. The goal of the ETG on Engineering Practice Documents is to develop detailed engineering practice documents (design guidance documents) on specific components of fire protection engineering. The intent is to research current materials, evaluate best available practices, and consolidate the information into guides that can be used to support practicing fire protection engineers in their everyday work.

The first project of the ETG on Engineering Practices is the development of a guide on Assessing Flame Radiation to External Targets from Liquid Pool Fires.[23] The document will include three sections: 1) Thermal Radiation from Pool Fires, 2) Radiant Ignition of Solids, and 3) Quantitative Methods for Skin Burn Simulation. Each section includes theory, calculation methods, and examples. Section I focuses on methods for determining the incident radiant flux at a target location. Section II focuses on the radiant ignition of solids. Section III focuses on quantitative methods to determine the effect on bare skin of a given radiant exposure. All sections include assessments of the accuracy of available methods and limitations on the use of the methods. Future editions of this guide will address additional targets.

3.3 SFPE Engineering Task Group on Performance-Based Analysis and Design

As previously indicated, the SFPE established the Engineering Task Group (ETG) on Performance-Based Fire Safety Analysis and Design to take the framework developed under this grant effort and expand it into a fundamental process-and-procedure document (framework document) describing a methodology for undertaking and reviewing performance-based fire safety analysis and designs. The resultant document will likely be called the *SFPE Engineering Guide for Performance-Based Fire Protection Analysis and Design*, and will be published by the National Fire Protection Association. Development of the guide is being supported by a grant from the National Fire Protection Association. The goal for the SFPE ETG on Performance-Based Fire Safety Analysis and Design is to have the guide completed by August of 1999. A draft of the guide will be available from the SFPE in January 1999 for review and comment by all interested parties.

4.0 Risk, Uncertainty, and Decision-Making Issues in Performance-Based Fire Protection Engineering

As introduced in the previous section, there are a variety of risk and uncertainty issues associated with performance-based fire protection engineering, as with most engineering processes, because all is not known about the materials and systems one uses, nor how things may change in the future. This gives rise to two distinct, yet inter-related issues: decision-making under uncertainty, and identifying and addressing "scientific" uncertainty in the engineering tools and methods utilized. To address the various types of uncertainty, decision analysis approaches, risk-based approaches, uncertainty analyses, or sensitivity analyses may be applied depending on the nature of the uncertainty. In some cases, when the uncertainties are indeterminate, it may be possible to address them only via regulatory (or other) control measures.

4.1 Terminology and Context

Many discussions of uncertainty make a distinction between two types: *aleatory,* which is uncertainty due to random variations and chance outcomes in the physical world, and *epistemic,* which is uncertainty due to a lack of knowledge.[24] These two types of uncertainty have also been described as randomness and imprecision,[25] as variability and knowledge uncertainty,[26] and as statistical uncertainty and engineering uncertainty.[27] For the purpose of this discussion, the terms variability and knowledge uncertainty will be used.

Although variability and knowledge uncertainty are different, when they are quantifiable, they can both be addressed using probabilities.[24] (It should be noted that some have argued that the only type of quantity whose uncertainty may be appropriately represented in probabilistic terms is an empirical quantity.[28]) Furthermore, when dealing with a single element in a population, both types of uncertainty may appear to be the same (lack of knowledge), and can often be characterized by a single probability (*e.g.*, the probability of failure).[26] In some cases, although uncertainty clearly exists, it may not be possible to distinguish it as variability or knowledge uncertainty. This is sometimes referred to as presenting *indeterminacy*[24] (indeterminate uncertainty).

When dealing with uncertainty (including variability, knowledge uncertainty, and indeterminate uncertainty), one of the most important challenges is to identify and focus on those uncertainties that matter in understanding the fire safety situation, and in making decisions about the fire safety tools, methods, and design options. Consider a fire protection engineering analysis of an office. Assume the goal is life safety, and the client loss objective is to "protect those occupants not intimate with the first materials burning from exposure to untenable conditions." There are numerous unknowns and uncertainties associated with this example. For example, how exactly can one predict where the room of fire origin will be? How exactly can one then predict the upper layer gas temperature in the room, or whether flashover will result? Even if flashover is prevented, how certain can one be that building occupants will not be exposed (or expose themselves) to untenable conditions? What engineering tools and methods are appropriate for the analyses? What performance criteria best suit the problem, and who should make that determination? At first glance, it is difficult to assess which of these uncertainties matter for the analysis and design process, let alone assessing to what degree they matter.

4.2 Framing Uncertainties in Terms of Acceptable Risk Decisions

One way to begin looking at the various knowledge gaps and sources of uncertainty is to view the fire safety problem as a risk or decision problem. Fire safety problems can be viewed as risk problems, as fire safety clearly deals with risk to people, property, business continuity, and damage to the environment. Moreover, fire safety problems can be considered "acceptable risk" problems, as one goal is to design fire safety measures that are "acceptable" to the stakeholder. To help frame the acceptable risk aspect of fire safety design, and to begin addressing the decision-making aspects thereof, one approach that can be considered is that of Fischhoff et al.[29]

The approach of Fischhoff et al. is based on the premise that an acceptable risk does not exist on its own, but rather, involves options that entail risk. In other words, an acceptable risk problem is a decision problem: different solutions to a risk problem provide different benefits, and acceptability is a function of the options available and the option(s) selected. Because values, perceptions, and available information may affect evaluation of the options, there are no universally accepted or acceptable risks. Thus, an approach to a risk problem is an attempt to solve or manage a problem, and whether a risk is acceptable is dependent on whether the approach to manage a risk problem is acceptable.

Fischhoff et al. outline three major approaches to decision-making that can be used for acceptable risk problems: Bootstrapping, Expert Judgment, and Formal Analysis.[30] The bootstrapping approach essentially involves identifying and continuing policies that have evolved over time. If a regulation, for example, has been deemed "successful," it is assumed that it has adequately balanced risks and benefits, and can provide a basis for establishing an acceptable level of safety or risk.[31] This is how most prescriptive-based building regulations have been developed. The expert judgment approach relies on the judgment of technical experts, knowledgeable in the field, to make critical decisions.[32] Such approaches are used in all aspects of building design, from structural engineering decisions to fire protection decisions. Formal analysis encompasses a broad collection of formalized decision-making tools and methods, including decision analysis and cost-benefit analysis. The assumption in this approach is that "intellectual technologies" can be used to help manage problems created by physical technologies. Although well-structured and presumed to be comprehensive, such approaches are often questioned as to their ability to accommodate all relevant consequences and options, as to their approaches to valuation (such as the value of a human life), and as to the rigor which is actually used in practice. [33]

Regardless of the approach taken, Fischhoff et al. identify five key "generic complexities" that need to be considered in resolving acceptable risk problems:[34] uncertainty about how to best define the decision problem, difficulties in assessing the facts of the matter, difficulties is assessing relevant values, uncertainties about the human element in the decision-making process, and difficulties in assessing the quality of the decisions that are produced. For this discussion, these generic areas will be discussed in terms of uncertainties about problem definition, uncertainties in science and engineering (uncertainties in assessing the facts of the matter), uncertainties about risk perception and values, uncertainties about the human element, and uncertainties in assessing the quality of decisions.

4.3 Uncertainties About Problem Definition

Performance-based fire safety analysis and design is a relatively new concept. As such, there can be significant differences in how it is perceived by engineers, authorities having jurisdiction (AHJs), and clients (e.g., building owners, other design professionals). If the differences are significant, or more importantly, if the differences are not addressed, the result can range from misunderstanding or confusion, to rejection of a seemingly appropriate candidate design alternative. Minimizing uncertainty in problem definition is especially important when undertaking an engineered approach to fire safety design outside of a performance-based regulatory system, where explicit goals, objectives, and criteria may not exist. Consider the current building regulatory system in the United States. Each of the three model building codes has a clause that indicates alternative methods and materials can be used when shown to be equivalent to those prescribed in the code in terms of strength, effectiveness, fire resistance, durability and safety.[35,36,37]

At first glance this may not seem to be a problem: the codes state that alternative designs can be accepted if shown to be equivalent. However, what does equivalent mean? How are the factors of strength, effectiveness, fire resistance, durability, and safety measured? Are these factors dependent on or independent from each other? What is an equivalent level of safety? These questions clearly point to the types of uncertainty in defining the problem, and how these questions are answered will affect the ultimate acceptance of an alternate material or method under the current regulatory system. As important as this step is, there is little guidance as to how these questions should be addressed in the current building regulatory process. (Discussion on decision-making approaches follows in a subsequent section.) This is one reason why it is so important for the engineer, the AHJ, and the client to come to agreement early in the analysis and design process.

4.4 Uncertainties in the Science and Engineering

In performance-based fire protection engineering, one of the key elements is the use of analytical tools to evaluate situations and predict likely outcomes. For the most part, these tools rely heavily on loss data, data from fire tests, and statistical data. Together, these tools and associated data are used to "scientifically" assess the facts of the matter, be they who or what is at risk, how the risk or hazard should be quantified, and how a candidate design provides an "acceptable" level of risk or safety.

When discussing the use of science in risk-based decision making, a report published by the United States' National Research Council (NRC) identified the following as criteria for judging success in "getting the science right:"[38]

> The underlying analysis meets high scientific standards in terms of measurement, analytic methods, data bases used, plausibility of assumptions, and respectfulness of both the magnitude and the character of uncertainty, taking into consideration limitations that may have been placed on the analysis because of the level of effort judged appropriate for informing the decision.

These are important concepts to remember in performance-based fire protection engineering. Without fire tests, fire test data, and product test data, and without fire growth correlations, calculations, and estimations, there could be no performance-based fire safety analysis and design. The testing provides information on how materials burn, can be inhibited from burning, and react to burning. The testing also provides a basis for developing physical and mathematical models of the burning: models that help one estimate or predict how materials may burn in a given situation. However, associated with fire testing, fire test data, fire effects model, and the use of fire effects models will be some amount of scientific uncertainty.

Scientific uncertainty has been characterized as containing the following elements:[39] conceptual uncertainty, theory uncertainty, model uncertainty, and data uncertainty. As used in Reference 39, conceptual uncertainty is concerned with the issue of whether the right questions have been asked. As used in this discussion, this factor is considered as part of uncertainty in problem definition. Theory uncertainty, as used here, is specific to the underlying theory upon which an analytical tool (model) is based. For example, a heat detector activation model based on a lumped mass approximation for heat transfer will have specific uncertainties related to the use of an approximation rather than use of the more theoretically accurate heat transfer relationships. Model uncertainty, as used here, encompasses a broad spectrum of model related issues, such as whether the equations are correct, whether they are the right ones, whether they are complete, and whether they have been programmed correctly (mathematical encoding). This particular area has been the source of much study.[13,14,21,40,41,42] Data uncertainty has also been the focus of much study, and includes such factors as choice of data (is there data, is there enough data, are there interpolation, extrapolation and interpretation issues), measurement uncertainty (measurement errors), and propagation of error (sensitivity of output to accuracy of input variables).[13,22,43,44]

4.5 Uncertainties About Risk Perceptions, Attitudes, and Values

As outlined earlier in this report, one of the first steps in a fire protection engineering analysis and design is to determine the fire safety goals and loss objectives. This involves determining what is important to the stakeholders, and to what lengths they are willing to go to provide protection. In some cases, the loss objectives are straightforward (*e.g.*, "I cannot afford to lose this process for more than 8 hours"), as are the project constraints (*e.g.*, "money is not an issue"). However, when life safety is the goal, it can be more difficult to develop specific loss objectives and to estimate the value of various candidate design alternatives. One reason for this difficulty relates to individual differences in risk perceptions, attitudes, and values.

There is no single perception or attitude about risk. Rather, there are a number of factors that affect an individual's or a group's perceptions and attitudes about risk. Uncertainties about risk perceptions are some of the most difficult uncertainties to quantify; however, they are among the most important uncertainties to address. Consider an engineer's request, of an AHJ, to approve an "alternative" fire protection design under the current building regulatory system. The client, for example, might be designing a building for which the current code appears to be "overly restrictive" with regard to the fire protection features required. The engineer may, after analysis of the situation, agree with the client and propose an alternative design. The AHJ must now decide whether the design is acceptable (within the scope of the regulations). What is at risk to the client, to the engineer, to the AHJ, and to the public? Furthermore, how does each party perceive their risk? These are important issues that should be addressed at the outset of the project, and for which various decision analysis approaches are available that could help.[45]

Uncertainty about values is closely related to uncertainties about risk perceptions and attitudes, as they are all important aspects of the "human equation" in the decision-making process, and they all impact the development of client loss objectives. The term *values*, as used here, relates to how one assigns worth in the usefulness or importance of something, and applies both to individual and societal issues. For this reason, uncertainties about values are often at the center of discussions about "how safe is safe enough?" This is an important subject, and readers are strongly urged to consult the references for more detailed discussions.[28,29,45,46]

4.6 Uncertainties About the Human Element

There is significant uncertainty associated with the human element in performance-based fire safety design: both from the perspective of how people react in fire situations,[47] to the ability to predict how future human actions might impact the design conditions (e.g., changing fuel loads in a room or building).[48,49] Some insight into uncertainties associated with human behavior can be seen in Canadian research on evacuation drills in seven apartment buildings.[50,51,52] In current performance-based fire protection designs, the time assigned by an engineer to the time interval required for people to begin evacuation can be zero (people are assumed to begin travel once the alarm sounds),[3,47] point values as low as 20 or 25 seconds,[53] or a multiplicative factor of the estimated travel time.[3] In the Canadian studies, however, it took people from 30 seconds to 14 minutes to start evacuating, with most of the people starting approximately three minutes after the alarm was sounded in buildings where the alarm was readily audible throughout.[50,51,52] Some of the delays can be attributed to not hearing the signal and not linking the signal to the threat of fire. In all buildings, some delays were related to people deciding what to do (e.g., looking in the corridor, looking for children, getting dressed, gathering valuables, etc.). In the evacuation of the World Trade Center following a bombing,[54] which involved a much larger and more complex series of buildings, there were remarkable similarities to the Canadian study. In the World Trade Center evacuation, for example, occupants did not initially consider the situation to be extremely serious. Delay between becoming aware of the event and first attempting to leave the building was common; the mean time between awareness of the event and attempting to leaving the building was 8.9 minutes in Tower 1 and 39.9 minutes in Tower 2. These two studies highlight some very significant concerns for fire safety engineers to consider: inaudible alarms clearly delayed the start of evacuation (audibility); people delayed evacuation further by actions such as verifying the signal or gathering personal effects (commitment); and occupants who did not hear the alarm did not move until the fire department arrived. Each of these factors has associated uncertainties which should be addressed in a performance-based fire safety analysis and design effort, and using no time values, single point estimates, or simple multiplicative factors may not be appropriate. (In all cases, the treatment of uncertainty should correspond to the analysis methods used.)

Regarding the inability to predict how people may change design conditions in the future, Brannigan has suggested that regulation is required to limit the options available to the engineers and to the building occupants.[48,49] In essence, the argument is that unless the decision-making options of building occupants can be controlled by regulation, it is inappropriate to allow building designs to be developed that allow people to make decisions, in exiting the building, that are contrary to the design assumptions and conditions. In this case, it is suggested that the indeterminate uncertainty associated with future human action cannot be addressed by the uncertainty factors alone, but requires regulation to minimize the uncertainty. Whether this is true or not, the fact is that there is considerable uncertainty associated with human decision making that should be accounted for in the performance-based fire protection design process.

4.7 Identifying Uncertainty in Performance-Based Fire Protection Engineering

As presented above, uncertainty in performance-based fire protection engineering has two central foci: uncertainty associated with the decision problems, and "scientific" uncertainty (e.g., models, data). Before one can address those sources of decision and scientific uncertainty that are important to the problem at hand, the potential sources of uncertainty must first be identified, and those sources of uncertainty that are important to the problem must be identified. Two approaches to identifying potential sources of uncertainty in performance-based fire protection engineering are outlined here: a decision analysis approach and a limit states approach.

4.7.1 Identifying Uncertainty by Characterizing Engineering Problems as Decision Problems

Engineering, by definition, is the art or science of making practical application of the knowledge of pure science.[55] The process of engineering (*i.e.*, the engineering method or approach taken) has similarly been defined[56] as a "strategy for causing the best change in a poorly understood or uncertain situation within the available resources." Combining the two definitions, it follows that an engineering problem involves the practical application, under uncertainty, of the best available information. Phrased another way, an engineering problem is a decision problem in the face of incomplete and uncertain information. If the premise that an engineering problem can be characterized as a decision-making problem is accepted, one can look to decision analysis to provide structure and support for solving engineering problems. As discussed above, in the case of performance-based fire protection engineering, the decision problem will be characterized by a broad set of issues, including problem definition, selection of analysis tools, methods, and data, risk perceptions, values, and costs.

To perform a complex engineering decision analysis,[‡] Notarianni and Fischbeck have proposed a methodology made up of three phases: deterministic, probabilistic, and informational.[57] In the deterministic phase, the decision problem is initially structured in a model where uncertainties in variables are ignored, and where the inputs are classified as decision variables (those variables a decision maker can control) and state variables (those variables beyond the control of the decision maker.) The purpose of this phase is to find the best setting for the decision variables while considering the best available information on the state variables. In the probabilistic phase, uncertainty is encoded on the crucial state variables, and risk preferences are addressed by selection of an outcome criterion that makes explicit the effect of value judgments. The "best action" is then determined based on the initial level of information (values and preferences of the decision maker), and a probabilistic sensitivity analysis is conducted. In the informational phase, the value of additional information is assessed by addressing two questions: should more

[‡] It should be noted that the methodology being developed is not limited to decision analysis problems; however, the referenced work focuses on this particular aspect. It is anticipated that work currently being undertaken in this area will provide a methodology for identifying and addressing uncertainties in all aspects of the performance-based fire safety engineering process.

information be gathered before acting on the main decision, and what is the worth (in monetary or other measures) of reducing uncertainty in each of the important variables in the problem? As the process is iterative, either a decision is made to act, or more information is gathered. If additional information is gathered, that information is fed back into the process.[57]

In the context of the above approach, one source of uncertainty will be associated with predicting the room of fire origin (state variable, part of problem definition). In some cases, this uncertainty may not have a large bearing on the outcome, whereas in other cases, it may be extremely important. To determine the importance, a systematic sensitivity analysis might be appropriate. To reduce the uncertainty, statistical methods could be applied to that data which already exists (*e.g.*, reported ignition sources and reported rooms of fire origin) for rooms of similar use and characteristics. Statistical analysis can also be used to identify what types of rooms, or types of occupancies, have experienced significantly more fires than other rooms or occupancy types. This will help identify those spaces for which special consideration might be warranted. It should be re-emphasized, however, that the uncertainty can never be completely eliminated, as conditions in a building may change over time, and it is not possible to know with certainty what those changes might be (e.g., there will likely be contents changes and perhaps physical changes as well). This should be considered during the decision process (perhaps as decision variables).

There is also uncertainty related to modeling fire growth and development, such as whether a given upper layer gas temperature will be reached and whether flashover will occur. In this case, there are a number of "quantities" (e.g., heat release rate, radiative fraction, ventilation openings), of various types (e.g., model inputs of empirical parameters or defined constants, index variables or model domain parameters related to the model structure, or selection variables such as outcome criteria, decision variables, or value parameters), which can be addressed using appropriate uncertainty treatments (e.g., probabilistic, parametric, switchover, expert judgment).[57] (These fall under the category of scientific uncertainty discussed earlier in this report.) For example, assuming the room of fire origin is known, the characteristics of the room (*e.g.*, geometry, interior finish) and its contents (fuel load) are known, and ignition has occurred, the upper layer gas temperature can be evaluated deterministically using engineering correlations and models.[§] Uncertainties about the room, the materials in the room, and the evaluation methods can be reduced by extracting relevant data from related fire tests or by performing well-instrumented fire tests on sample representative contents, in various configurations, in similar rooms. In the absence of actual fire test data and loss statistics, subjective probabilities can be obtained from those with expertise in the area.[58] By addressing the scenario-related uncertainties in this manner, the scenario can be better described and evaluated.

[§] In trying to explain or predict why or how something may happen, one often relies on the use of models (physical and/or mathematical). In one sense, a model is a representation of an observed event. When based on a well-founded rule, law, or correlation, a model can be used to predict the reoccurrence or repetition of a similar event in the future (*e.g.*, one can predict what phase the moon will be in at some point in the future based on Newton's laws of motion). Where the rules or laws are not well founded, are not well understood, or do not exist, the effectiveness of a model to predict the future is lessened and the uncertainties are greater and more difficult to quantify (such as the case where future events may be impacted by the unpredictable actions of people). In essence, it is easier to identify, quantify, and address uncertainties in physical systems than in situations in which people are integrally involved. (See Reference 11 for an excellent discussion on uncertainty, explanation, and prediction.) This distinction is important to remember in performance-based fire protection analysis and design, and affects the certainty of predictions made regarding the level of fire safety provided in the future.

4.7.2 *Identifying Uncertainty in Fire Protection Engineering Using a Limit States Approach*

In a somewhat different approach, it may be possible to structure a performance-based fire protection engineering problem in the form of a limit states equation, as is done for some structural engineering analysis. Lucht, for example, has suggested that a limit states relationship, which implies that the fire safety strength of a building must be greater than the sum of the fire-related loads acting upon it, can be developed for fire protection engineering.[59] In concept, Lucht's relationship provides a potential approach for identifying and evaluating the ability of physical building fire safety features (e.g., compartmentation, detection systems, suppression systems, and egress systems) to withstand the various fire loads applied (e.g., heat, smoke and carbon monoxide). However, it is not clear how Lucht's relationship addresses the human aspect, a significant source of uncertainty in fire safety design (e.g., uncertainty about future human actions). In addition, Lucht's relationship does not provide a common metric for analysis (i.e., it is not clear that the heat, smoke, and carbon monoxide loads are expressed in the same units of measure). To address these concerns with Lucht's limit state relationship, a time-based relationship for fire safety analysis and design is suggested.[60]

Time is suggested as a common metric as it appears to be universally accepted for assessing fire safety design. It is a valid metric for the evaluation of fire growth and impact (e.g., time to reach a certain upper layer temperature, time to reach a certain smoke density level, and time to reach flashover), of the building fire safety measures (e.g., time until fire detection, time until fire suppression agent is applied, and time until structural elements fail), of the building occupants (e.g., time to respond to a fire cue and time to reach a place of safety) and of the fire department (e.g., time of notification, response time, and attack time).

To develop limit state equations for fire safety design, there first needs to be a clear understanding of fire safety goals and objectives, and the criteria by which fire safety designs will be evaluated in their ability to meet the goals and objectives. These items will either come from regulatory documents (i.e., codes and standards) or be developed on a project specific basis. For illustrative purposes, and as a basis for the development of limit state equations for fire safety design, consider the following.

Assume a fire safety objective of providing adequate time for those occupants who are not intimate with the first materials burning to reach a place of safety without being overcome by the effects of the fire. This objective can effectively be reduced to a time-dependent relationship that could form the basis of a limit states analysis: *the time required for those occupants not intimate with the first materials burning to reach a place of safety must be less than the time until conditions in the means of egress become untenable.* This is a classic relationship for "available safe egress time," and can be expressed as $E < H$, where, E represents the time required to egress (reach a place of safety), and H represents the time until hazardous (untenable) conditions are reached.

Applying the concept of uncertainty factors, one can expand this relationship as follows:

$$\lambda\phi E < \sum_{i=1}^{n} \gamma_j H_j$$

where

ϕ = Uncertainty factor related to time required to egress
γ = Uncertainty factor related to time until hazardous conditions

As in structural engineering, this relationship can be further resolved into individual variables, in this case related to egress time and the time until untenable conditions are reached, and additional uncertainty factors can be included as well. For example, a variety of human behavior factors may affect the egress time, E, including the time to recognize a fire threat and the time it takes an occupant to decide to begin evacuating. There are also a variety of occupant characteristics that should be considered, including age, mobility, affiliation, and role.

Similarly, one can resolve the time to reach untenable conditions, H, into such components as the time required to reach a given upper layer temperature, to reach a given radiant heat flux level, to reach a given visibility (in terms of upper layer depth or percent obscuration), or to reach a given concentration of toxic products. The factors that describe the time to reach untenable conditions are the performance and design criteria (the criteria that will be used to demonstrate the proposed designs comply with the goals, objectives, and requirements).

To evaluate the performance and design criteria, a number of relationships will be required (one for each design criterion). These relationships will take the following form (the following is for the upper layer temperature design criterion only):

$$\phi_{FD}t_{FD} + \phi_{PM}t_{PM} + \phi_{OM}t_{OM} < \gamma_{UT}t_{UT}$$

where

t = Time
ϕ = Uncertainty Factor (Egress)
FD = Fire Detection
PM = Pre-Movement
OM = Occupant Movement
γ = Uncertainty Factor (Hazard)
UT = Upper Layer Temperature (Design Criterion)

This relationship simply states that, for occupant egress to be successful, the sum of the fire detection, pre-movement and movement times must be less that the time for the upper level temperature design criterion to be reached. Should more detailed analysis be required, each of the above time components can be further resolved into more fundamental components, and design factors can be added to account for design-specific conditions. For example, the time required for pre-movement and movement, $\phi_{PM}t_{PM}+\phi_{OM}t_{OM}$, could be further resolved as follows:

$$\phi_{PM}t_{PM}+\phi_{OM}t_{OM} = C_{AG}C_{AF}\,C_C\,(C_{AU}\phi_{OR}t_{OR} + \phi_{OD}t_{OD} + C_M\phi_{OM}t_{OM})$$

Each factor on the right-hand side relates to egress time and the human factors that may affect it. In this example, the fundamental time components are given as occupant recognition time, OR, occupant decision time, OD, and occupant movement time, OM. Associated with each of these time components is an uncertainty factor, ϕ, which is used to adjust for uncertainties in the response-time values selected. Each of these time components may be resolved into even more basic components (e.g., travel speed on horizontal surfaces and on stairs) if necessary. In addition, variability factors are added to adjust for design-specific concerns:

- The age factor, C_{AG}, may be required when it is necessary to account for the slower response and travel time of infants and elderly.
- The affiliation factor, C_{AF}, may be required when it is necessary to adjust the egress time to account for such factors as searching for family members or waiting for someone else to take action.
- The commitment factor, C_C, may be required when it is necessary to adjust the egress time to account for delays in response due to such factors as being committed to finishing an ongoing activity, getting to a meeting on time, or making sure that all the lights are off before one leaves a residence.
- The audibility factor, C_{AU}, may be required when it is necessary to adjust the recognition time based on the audibility of alarm signaling appliances.
- The mobility factor, C_M, may be required when it is necessary to adjust the egress time for the mobility impaired.

Although preliminary investigation suggests such a time-based relationship could be applied to the entire fire protection engineering process, significant research and development is required before such a relationship could be widely used. First, it must be demonstrated that the entire performance-based fire protection engineering process can be described in this manner. This will require analysis of all aspects of fire protection engineering to determine if, in fact, time is an appropriate metric. Second, research and development efforts are required to quantify the variability, knowledge uncertainty and indeterminate uncertainties. This will require statistical analyses, deterministic analysis, and human behavior and decision-making analysis. (Although some efforts are already underway to identify and quantify uncertainty in fire protection engineering,[26,57] much more effort will be required.) The decision-making analysis, in all likelihood, will be related to risk perceptions amongst various sub-sets of building occupants and users (e.g., homeowners, employees, the visiting public). Finally, the approach must be able to identify which sources of uncertainty are dominant, cull out those which are unimportant, and ensure that unwarranted addition or multiplication of uncertainty factors does not result.

Even if such an approach can be shown to be useful in identifying and addressing uncertainties in the fire protection engineering process, it may be unwieldy for use in practical design applications. In the end, application of such an approach may be appropriate simply for identifying potential sources of uncertainty in performance-based fire protection engineering, and may require the use of different approaches to address those sources of uncertainty important to a specific problem.

4.8 Assessing the Quality of Decisions

The final aspect to the discussion of risk and uncertainty is assessing the quality of the decisions made. Fischhoff et al. outline a number of methods for analyzing the quality of decisions, including sensitivity analyses, error theory, convergence validation, and track record.[61] Under the current regulatory system and state of fire protection engineering practice, the quality of decisions made is reflected in codes and standards, and in fire losses to people, property, mission, and the environment. This is the track record approach. It will be left to the readers to decide for themselves if the quality of current decisions is acceptable. With regard to the formal decision analysis approaches, only sensitivity analysis will be outlined here. In general, this is an area that can benefit from additional research and application to performance-based fire protection design.

A sensitivity analysis is a study of how changes in one or more parameters of a method or model affect the results of the method or model. Such analyses are important in that any method or model may be sensitive to uncertainties in the theories utilized, uncertainties in the input data, or any of the other uncertainties discussed previously. The intent of a well-designed and properly executed sensitivity analysis is to identify the dominant variables in the method or model, define the acceptable range of values for each input variable, demonstrate the sensitivity of output variables to variations in input data, and inform and caution potential users about the degree and level of care to be taken in selecting and using the method or model.[13]

With regard to computer fire model evaluations, an analysis of internal parameters will provide insight as to how well the physics and mathematics of the model reflect real fire behavior. These parameters should be verified by the model developer prior to widespread use of the model. An analysis of the external parameters will provide insight as to how changes in the model inputs will affect the model results. This analysis should be performed by the model user. Typical external parameters include compartment characteristics, ventilation characteristics, fuel characteristics, thermophysical boundary characteristics (*e.g.*, conductivity of ceiling and wall materials), fire detection and suppression device type and operating temperatures, and in most cases, initial heat release rates and fire growth characteristics (*e.g.*, slow, medium, fast, ultrafast).

4.9 Summary

Issues of risk, uncertainty, and decision-making are interwoven throughout the process of performance-based fire protection analysis and design. Although these areas have received attention in other fields, additional efforts will be required to better understand and address them in performance-based fire protection analysis and design if widespread acceptance of the performance-based approach is to be expected. Two possible approaches have been briefly considered: addressing performance-based fire protection analysis and design problems as decision problems, and addressing performance-based fire protection analysis and design as a limit states problem. Although both approaches appear to have merit, neither have been developed fully enough for consideration as practical tools at this time.

5.0 Summary and Future Work

Efforts undertaken towards assessing the technological requirements for realization of performance-based fire safety design in the United States performed under this grant have:

1. Identified a working definition of performance-based fire safety analysis and design,
2. Reviewed performance-based fire safety analysis and design methods in development or use around the world,
3. Elicited consensus on the need for, and the structure of, a performance-based building regulatory system for the United States,
4. Resulted in a framework for a performance-based fire safety analysis and design approach for use in the United States,
5. Determined that evaluation of fire protection engineering tools and methods, on their use, application, and limitations, is needed for wide spread acceptance of the tools and methods in a performance-based system,
6. Supported efforts for evaluating fire protection engineering tools and methods and reporting on their uses, applications, and limitations, and
7. Focused attention on the need to better address issues of risk, uncertainty, and decision-making in performance-based fire safety analysis and design.

As a result of these efforts, indications are that wide spread acceptance of performance-based fire safety analysis and design will be possible throughout the United States when a sufficient percentage of the components of a performance-based regulatory system are in place. As discussed by the focus group, the components of a performance-based regulatory system include a code, acceptable engineering standards and practices, and acceptable evaluation tools and methods.

The development of a guide for performance-based fire safety analysis and design, the evaluation of the computer model DETACT-QS, and the development of an engineering practice document on thermal radiation hazards are good first steps for the fire protection engineering community. However, there is much more to be done:

1. The evaluation of fire effects models needs to continue, and reports need to be issued on their use, application, and limitations.
2. The development of engineering guides and practices on specific fire protection engineering issues needs to continue, and they need to be widely available and accessible to practitioners.
3. The collection, storage, and common accessibility to data for use in model evaluations, and for use in fire safety analysis and designs, is paramount.
4. More research and development is warranted on the issues of risk, uncertainty, and decision-making related to performance-based fire safety analysis and design. This area is particularly important in that acceptance of the tools, methods, and concepts will ultimately rely, at least in part, on the confidence of the building and fire communities on the appropriateness, effectiveness, and reliability of the tools and methods. In addition, the more the area of risk and uncertainty is studied, the more gaps are identified in knowledge needed for performance-based fire safety analysis and design (e.g., knowledge regarding human behavior in fires).

Furthermore, complete integration of performance-based fire safety design into the United States' building and fire communities requires much more than technology assessment and development:

- The ongoing education of engineers and building and fire authorities is necessary for the transfer of knowledge to those individuals who will develop and approve performance-based designs.
- To ensure that the methods and tools integrated into the regulatory system adequately address the public's perceptions of risk and liability, research in the area of public policy is needed.
- Finally, regulatory infrastructure support is required to introduce the concepts of performance-based design tools and methodologies into building codes and insurance requirements and to ultimately gain the acceptance of these tools and methodologies within the United States' regulatory system.

If future support is available to address these issues, the widespread integration of performance-based fire safety design approaches into the United States can be realized.

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Performance-based fire safety design methods are being used or developed in many parts of the world. The bases of several of these methods are the many fire engineering tools and methods developed in the United States. Unfortunately, these tools and methodologies are not being widely applied within the United States. There are many reasons for this, including the lack of performance-based fire and building codes in general use, and, were there are such codes or regulations, the lack of documentation on the availability and application of credible fire protection engineering tools and methodologies for fire safety design. To help assess the technological requirements for realization of performance-based fire safety design in the United States, the Society of Fire Protection Engineers, under a grant from the National Institute of Standards and Technology, Building and Fire Research Laboratory, conducted a research effort during the period September 1995 through August 1998. During Phase I of this effort, the intent of a performance-based approach to fire safety analysis and design from around the world were identified and evaluated for applicability in the United States, and a framework for a performance-based approach to fire safety analysis and design for use in the United States was outlined. During Phase II of this effort, a focus group was convened to discuss concepts of a performance-based building regulatory system for the United States, including the role of engineering tool sand methodologies in a performance-based system, and support was provided for the evaluation of engineering tools and for the development of engineering practice documents. During Phase III of this effort, the development of an engineering guide on performance-based fire protection analysis and design was begun, continued support was provided for the evaluation of engineering tools and for the development of engineering practice documents, and issues related to risk and uncertainty in a performance-based fir safety design environment were investigated. This report summarizes the activities of this three-year effort, and outlines future efforts required for widespread realization of performance-based fire safety design in the United States.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

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