



Performance-Based Codes & Standards Preparation Primer

REVISION 1.0 21 JANUARY 2000

© National Fire Protection Association, 1999

National Fire Protection Association
1 Batterymarch Park
Quincy, MA 02269-9101 USA

Preface

This primer has been developed by the NFPA Performance-Based Support Team (PB Support Team). The PB Support Team functions under the auspices of the NFPA Standards Council, and reports directly to the Council on an on-going basis. The PB Support Team was created in 1995 to assist NFPA Technical Committees with the transition to performance-based documents.

This document results from a combination of earlier primers produced as a series intended to provide NFPA Technical Committees with guidance and information on how to write a performance-based NFPA code, standard, or similar document. This primer is based on the report of the NFPA In-House Task Group on Performance-Based Codes and Computer Fire Models' entitled *NFPA's Future in Performance-Based Codes and Standards*. This report, released in July 1995 and developed in conjunction with the NFPA Board of Directors, implies the need for the development of further guiding information for NFPA Technical Committees.

It is anticipated that this primer will undergo future changes as they are developed. Any comments on the primer should be sent to:

NFPA
Attn.: Standards Council Secretary
1 Batterymarch Park
Quincy, MA 02269-9101

Table of Contents

PART I - INFORMATION	1	6-4 DEVELOPMENT OF PERFORMANCE CRITERIA	21
Chapter 1 General Information	1	PART IV - PERFORMANCE-BASED INPUT AND VERIFICATION	22
1-1 PRIMER PURPOSE	1	Chapter 7 Design Specifications in Performance-Based Design	22
1-2 PRIMER SCOPE	1	7-1 GENERAL	22
1-3 ORIGIN	1	7-2 DEFINITION	22
1-4 PROCESS	1	7-3 BUILDING DESIGN SPECIFICATIONS	22
1-5 CLARIFICATION	1	7-4 FIRE PROTECTION DESIGN SPECIFICATIONS	22
Chapter 2 Glossary	4	7-5 DESIGN SPECIFICATION DOCUMENTATION	22
2-1 GENERAL	4	Chapter 8 Development of Characteristics for Performance-Based Design	23
PART II - PERFORMANCE-BASED FRAMEWORK	8	8-1 GENERAL	23
Chapter 3 Overview of Performance Approach	8	8-2 OCCUPANT CHARACTERISTICS	24
3-1 PERFORMANCE VERSUS PRESCRIPTIVE	8	8-3 BUILDING CHARACTERISTICS	25
3-2 PERFORMANCE-BASED CODE AND STANDARD DEVELOPMENT	10	8-4 DOCUMENTATION	25
3-3 PERFORMANCE-BASED DESIGN INTENTIONS	14	Chapter 9 Assumptions	27
3-4 DESIGN INPUT AND VERIFICATION	14	9-1 GENERAL	27
3-5 DESIGN ACCEPTANCE AND APPROVAL	17	9-2 ROLE OF ASSUMPTIONS	27
PART III - PERFORMANCE-BASED DESIGN INTENTIONS	18	9-3 ASSUMPTION CONSISTENCY	27
Chapter 4 Goals	18	9-4 ASSUMPTION REGARDING PRESCRIPTIVE REQUIREMENTS	27
4-1 GENERAL	18	9-5 DESIGN ASSUMPTIONS	27
4-2 DEFINITION	18	9-6 BUILDING FEATURES AND SYSTEM PERFORMANCE	28
4-3 PERFORMANCE-BASED FIRE SAFETY GOALS	18	9-7 ASSUMPTION DOCUMENTATION	28
4-4 DEVELOPMENT OF FIRE SAFETY GOALS	19	Chapter 10 Fire Scenarios in Performance-Based Design	29
Chapter 5 Objectives	20	10-1 GENERAL	29
5-1 GENERAL	20	10-2 DEFINITION	29
5-2 DEFINITION	20	10-3 DESIGN FIRE	29
5-3 DIFFERENCE BETWEEN GOALS AND OBJECTIVES	20	10-4 SCENARIO CONSISTENCY	29
5-4 PERFORMANCE-BASED FIRE SAFETY OBJECTIVES	20	10-5 SCENARIO APPLICATION	29
5-5 DEVELOPMENT OF FIRE SAFETY OBJECTIVES	20	10-6 SCENARIO SELECTION	30
Chapter 6 Performance Criteria	21	10-7 SCENARIO CONSTRUCTION	31
6-1 GENERAL	21	10-8 PERFORMANCE-BASED PROVISION DEVELOPMENT	32
6-2 DEFINITION	21	10-9 CONCLUSION	33
6-3 PERFORMANCE-BASED FIRE SAFETY PERFORMANCE CRITERIA	21	Chapter 11 Design Verification	34
		11-1 DESIGN VERIFICATION	34
		11-2 VERIFICATION METHODS	35
		11-3 VERIFICATION METHOD SELECTION	38

PART V – DESIGN ACCEPTANCE AND APPROVAL	39
Chapter 12 Design Acceptance	39
12-1 GENERAL	39
12-2 DESIGN OUTPUT	39
12-3 UNCERTAINTY IN PERFORMANCE-BASED FIRE SAFETY	39
Chapter 13 Reliability	41
13-1 GENERAL	41
13-2 DEFINITION	41
13-3 ROLE OF RELIABILITY IN PERFORMANCE-BASED DESIGN	41
13-4 METHODS OF ADDRESSING RELIABILITY	42
13-5 INCORPORATION OF RELIABILITY IN CODES AND STANDARDS	44
Chapter 14 Documentation	46
14-1 DESIGN DOCUMENTATION AND PRESENTATION	46
14-2 DESIGN REPORT	46
14-3 SPECIFICATION AND DRAWINGS	46
14-4 OPERATIONS AND MAINTENANCE MANUAL	46
Chapter 15 Approval Process	48
15-1 GENERAL	48
15-2 DESIGN APPROVAL	48
15-3 BUILDING MAINTENANCE AND RISK MANAGEMENT	48
15-4 MANAGEMENT OF CHANGE	49
PART VI - TECHNICAL COMMITTEE USE	50
Chapter 16 Technical Committee	50
16-1 GENERAL	50
16-2 PERFORMANCE-BASED DOCUMENT DEVELOPMENT	50
16-3 USING THE PERFORMANCE-BASED OPTION	50
16-4 PERFORMANCE-BASED DESIGN GUIDE	50
Appendix A	51
Appendix B	66

NFPA Performance-Based Primer

Codes & Standards Preparation 1999 Edition

NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates explanatory material on that paragraph in Appendix A.

PART I - INFORMATION

This section (Part I) provides general information to the Technical Committee regarding the Primers and terms used within the Primers.

Chapter 1 General Information

1-1 Primer Purpose. The purpose of this primer is to serve as a resource for NFPA Technical Committees during their efforts in developing performance-based provisions and incorporating them into NFPA documents. This primer can be used to develop new stand-alone performance-based documents or to develop performance-based options in existing or future documents. "Document" is used as a collective term for codes, standards, guides, or recommended practices and can refer to any of the four. Additionally, throughout this primer, the term "Performance-Based Document" is used. This phrase includes documents that are either entirely performance-based, or a combination of performance and prescriptive provisions.

1-2 Primer Scope. This primer provides a general, comprehensive overview of the performance-based approach, which can be used by NFPA Technical Committees as a framework to develop a performance-based option within a code or standard, or a stand-alone performance-based document. This document is meant to provide general guidance on the performance-based approach, while also providing an elaboration on specific topics which should be addressed in writing or in concept by any Technical Committee interested in developing a performance-based document. This primer is a compilation of six previously produced, stand-alone primers that serve as resources for NFPA Technical Committees for the development of performance-based provisions.

1-3 Origin. This primer is the direct result of the efforts of the NFPA In-House Task Group on

Performance-Based Codes and Computer Fire Models and the report they produced.¹ This document is based in part on that report and provides an expansion of the concepts contained therein. It is anticipated that the primer will undergo future changes as they are developed.

1-4 Process. As shown in Figure 1-4 (Included on Following Page), there are two distinct, although not exclusive, approaches to developing performance-based provisions. The top-down approach is described in the NFPA in-house task group report and the bottom-up approach is taken from a report from the Canadian Codes Centre on bottom-up analysis.²

A total of six stand-alone primers have been completed, with these documents combined to produce this master document:

Table 1-4. Stand-alone Primers

Primer #	Title	Status
1	Goals, Objectives & Criteria	Available
2	Characteristics & Assumptions	Available
3	Fire Scenarios	Available
4	Performance-Based Verification Methods	Available
5	Reliability	Available
6	Overview of Performance Approach	Available

Additional Primers may be developed as needed to address topics, e.g., computer fire modeling, risk management, etc.

1-5 Clarification.

1-5.1. Due to the wide variety of topics covered by NFPA documents, it is difficult to address each topic specifically in this primer. These topics include buildings, systems within buildings, building features, vehicles (including boats and ships), outdoor property, people, and products. Therefore, in this primer "building" will be used to generally indicate the topic or scope of a given NFPA document.

1-5.2. NFPA performance-based codes and standards are intended to be dual track and they will contain both prescriptive and performance-based provisions. However, guides may be entirely performance-based. Because of this, “performance-based document” will be used in a generic sense to refer to any NFPA document containing performance provisions.

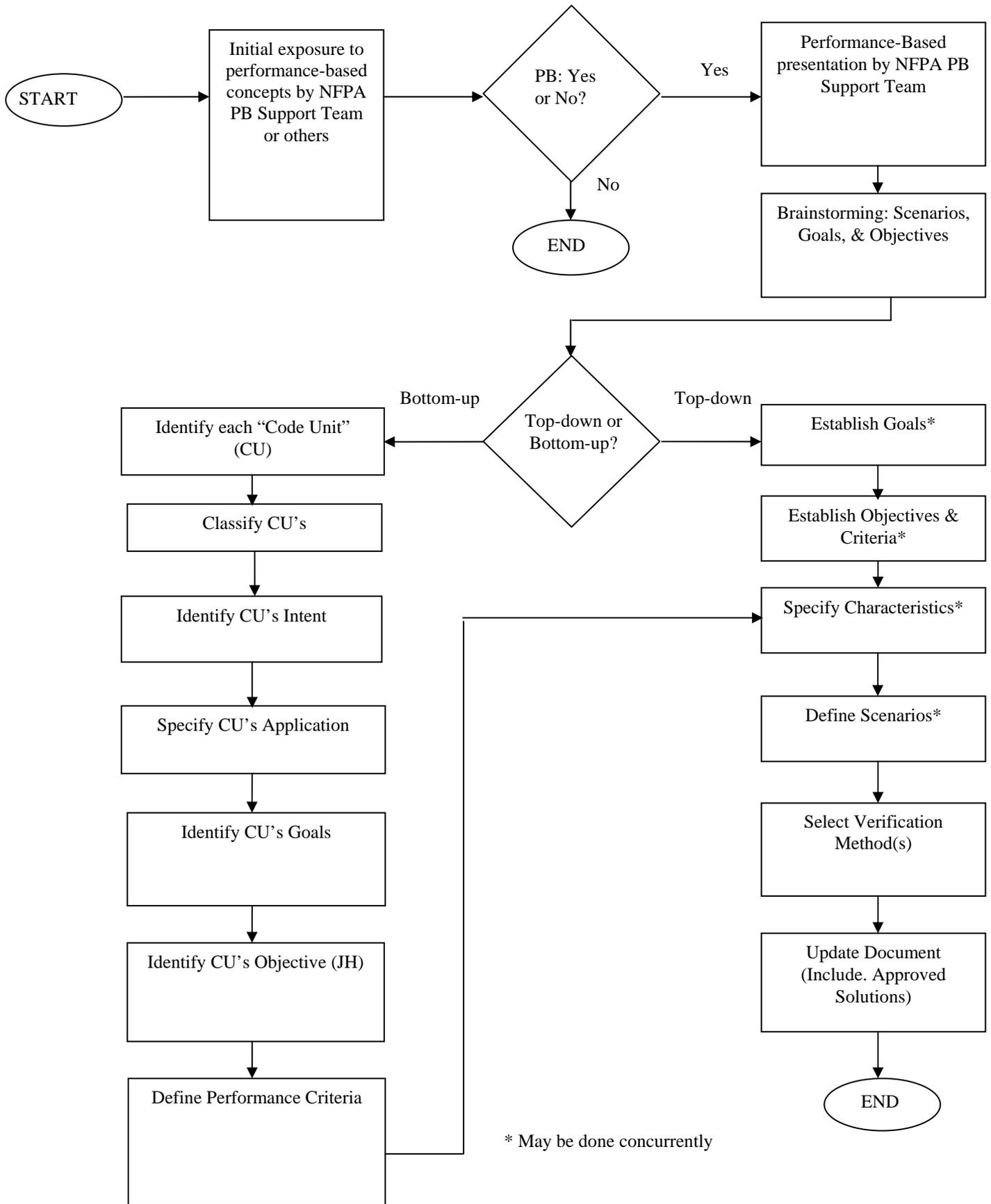


Figure 1-4. Performance-Based document development

Chapter 2 Glossary

2-1 General. The following terms are presented to help provide a consistent vocabulary. Definitions of the following terms are taken from the NFPA in-house task group report, unless otherwise noted.

Acceptable. That which has adequately satisfied specified performance criteria. The AHJ holds the final decision on whether or not a design or portion of a design is acceptable.

Approved Method. Authoritative procedure used to develop proposed solutions. A more commonly used example of approved methods are contained within prescriptive documents.

Assumptions. Specifications related to the building, ambient conditions, and surroundings, which do not vary across individual fire scenarios. Examples include ambient pressure and temperature in the building, or fire department response.

Authority Having Jurisdiction. The organization, office, or individual responsible for approving equipment, an installation or a procedure.

NOTE: The phrase “authority having jurisdiction” is used in NFPA documents in a broad manner because jurisdictions and approval agencies vary, as do their responsibilities. Where public safety is primary, the authority having jurisdiction may be a federal, state, local or other regional department or individual such as a fire chief; fire marshal; chief of a fire prevention bureau, labor department, or health department; building official; electrical inspector or others having statutory authority. For insurance purposes, an insurance inspection department, rating bureau, or other insurance company representative may be the authority having jurisdiction. In many circumstances, the property owner or his or her designated agent assumes the role of the authority having jurisdiction; at government installations, the commanding officer or departmental official may be the authority having jurisdiction.

Bottom-Up.* One approach used to develop performance-based provisions. Using this approach, the goals, objectives, characteristics, and scenarios of a document that are unstated prior to document revision processing are identified and explicitly stated.³ See "Top-down".

Calculation Method.* A description of a system or phenomenon in terms of relationships among elements, permitting study of how some elements vary when other elements are changed. A calculation method normally consists of one or more mathematical relationships, permitting calculation of some elements based on their relationship(s) to other elements. Note that fire science and engineering use "model" as a synonym to calculation method but also for other concepts and elements such as scale models.

Computer Model. A calculation method that is packaged as computer software.

Fire Effects Model. A calculation method that incorporates engineering and scientific principles and applies them in a logical manner to determine possible consequences and extent of physical effects based on an externally specified fire, expressed as heat release rate as a function of time. (Typically referred to as a "fire model", even though it may not model combustion.)

Evacuation/Egress Model. A calculation method used to describe the behavior and movement of people during a fire situation. May be used in combination with a fire effects model to determine whether or not occupants safely escape from a building before being exposed to products of combustion.

Computer Fire Model. A calculation method that is packaged as computer software and used to predict fire behavior.

Characteristics. Qualities of the occupants, building contents, potential fuel packages, process equipment, and facility features and systems. The focus is usually on those characteristics that should be considered when developing a performance-based fire protection design or performance-based provisions for NFPA documents.

Code (Document) Unit. The smallest portion of a code (i.e., a document) that can have an intent and application statement attached to it.⁴ Each code unit is a definable concept having a type, an intent,

application (e.g., “application and limitations of the application of the provision such as occupancy, building height, sprinklered/nonsprinklered building, etc.”) and one or more objectives.

Design Fire. Component of a fire scenario, consisting of a detailed description of the fire, but excluding any outside conditions or factors regarding the building occupants and other aspects of the design that may impact the fire development and/or severity. This description of the fire should include crucial information such as the fire’s size, growth rate, heat release rate, and other related fire properties.

Design Specification.* The aspects of the building design which will impact the fire safety analysis, such as floor area and layout, sprinkler density, building height, ventilation system flow rate, etc. expressed in engineering units.

Design Team. Group of stakeholders including, but not limited to, representatives of the architect, client, and any and all pertinent engineers and other designers. A stakeholder is an individual, or representative of same, having an interest in the successful completion of a project.

Fire Safety Goal. Overall outcome to be achieved with regard to fire. Goals are non-specific and are measured on a qualitative basis. They should be stated in terms of conditions that are intrinsically desirable and do not rely on any assumptions. Goals should be stated in terms that are potentially measurable, even if the precise measurement scale is not specified. Thus, goals may be expressed in terms of impact on people, property, or the environment, or in terms of mission continuity. A single goal may be applicable to many different NFPA documents.

Fire Scenario. Quantitative description of a fire and any factors affecting or affected by it from ignition to extinguishment; including ignition sources, nature and configuration of the fuel, ventilation, characteristics and locations of occupants, condition of the supporting structure, and conditions and status of operating equipment and fire protection systems. Usually used more narrowly to describe initiating conditions for use with a model, test procedure, or other method used for deriving conditions at later stages. The term "design fire" is used even more narrowly to refer to initiating conditions of the fire, those thus excluding most characteristics of the larger

building environment the fire may grow into, occupants, and building systems and features.

Functional (or Performance) Requirement. A statement indicating how the building (system, etc.) must perform in order to achieve the stated objectives and goals; typically, a further refinement of an objective, if needed. For example, to achieve the life safety goal with a smoke control objective, a functional requirement could be “The level of smoke shall remain above the heads of evacuees using either a natural or forced ventilation smoke management system.”

Owner. The party who holds financial responsibility for the project and to whom professional services are rendered.

Performance-Based Design Approach. A design process whose fire protection solutions are designed to achieve a specified goal for a specified use or application. This process allows performance-based documents to be implemented and insures that their goals are met.

NOTE: The following describes a performance-based design approach:

- a) Establish fire safety goals.
- b) Evaluate the condition of the occupants, building contents, process equipment, or facility in question with regard to fire protection.
- c) Establish performance objectives and performance criteria.
- d) Identify potential hazards to be protected against.
- e) Define appropriate scenarios.
- f) Select suitable verification methods (e.g., fire models).
- g) Develop trial solutions.
- h) Assess proposed solution.
- i) Document proposed solution along with supplementary information.
- j) Obtain approval of the proposed solution.

Steps a) through f) are also part of the development of a performance-based code or standard. Only steps g) through j) are specific to performance-based design, where the intent is to find a solution for the project. Also, steps c), d), and e) are not necessarily intended to be sequential; they may in fact be concurrent. While the above is presented in a sequential order, the design approach does not necessarily need to begin with step a) and proceed

consecutively through step j). Since different stakeholders (e.g., owner, designer, authorities) must be satisfied, some steps of this approach are iterative. Similarly, for performance-based document development, steps a) through e) may or may not be taken sequentially.

Performance-Based Document. A code, standard, or similar document that specifically states its fire safety goals and references approved methods that can be used to demonstrate compliance with its requirements. The document may be phrased as a method for quantifying equivalencies to an existing prescriptive-based document and/or it may identify one or more prescriptive documents as approved solutions. Furthermore, the document allows the use of all solutions that demonstrate compliance using approved methods.

NOTE: A performance-based document may also include separate prescriptive provisions as a parallel, independent approach to meet the performance-based goals and objectives.

Performance Criteria. Performance objectives for individual products, systems, assemblies, or areas that are further quantified and stated in engineering terms (e.g., temperature, radiant heat flux, level of exposure to combustion products). Performance criteria provide pass/fail threshold values which are treated as data for calculations used to qualify a proposed performance-based solution.

Performance Objective. Requirement for the fire, building, or occupants (or combination thereof) that must be satisfied in order to achieve a fire safety goal. Objectives are stated in more specific terms than goals and tend to be more quantitative than qualitative. Objectives may be thought of as specific goals for individual NFPA documents

Prescriptive-Based Document. A code or standard that prescribes fire protection for a generic use or application. Fire protection is achieved by specifying certain construction characteristics, limiting dimensions, or protection systems without providing a mechanism for how these requirements achieve a desired fire safety goal. Typically these documents do not state their fire safety goals.

NOTE: Many current NFPA codes and standards are not strictly performance-based or prescriptive-based: technically, they can

be referred to as prescriptive documents containing some performance provisions. For example, a requirement for a one-hour door sets a measurable performance criterion, going beyond prescription of the door's construction, but does not link the criterion explicitly to a fire safety goal.

Project Team. The design team and the Authority Having Jurisdiction. The AHJ may have no formal or legal responsibility for the design but should be involved at every stage of the project. This ensures the greatest chance for a successful project.

Proposed Solution. A fire protection system design intended to achieve the stated fire safety goals and which is expressed in terms that make it possible to assess whether the fire safety goals and objectives have been achieved. If models are used, then the proposed solution should also specify the models and input data employed.

Safety Factor. Adjustment made to reflect conservatism due to uncertainty in the methods and assumptions employed in measuring performance. A safety factor is not part of the process of setting acceptable levels of safety as a function of allowable risk, as it only reflects the uncertainty regarding the precision of the calculation.

Scenario Data. Specific data, related to each design fire scenario and expressed in engineering terms or conditions, which can be used as input for the design tool or verification method by the designer. The scenario data should be those aspects of the fire scenario relating to the fire itself, including, but not limited to the design fire, fire location, and any other aspects of the fire that need to be input into the verification method being used by the designer.

Top-Down. One approach used to develop performance-based provisions. Using this approach, the goals and objectives are developed during document revision processing without consideration of any current prescriptive requirements: a “clean sheet of paper” approach. See “Bottom-up”.

Verification. Confirmation that a proposed solution (i.e., candidate design) meets the established fire safety goals. Verification involves several steps. Verification confirms that the building is built as proposed to a design that will achieve the intended level of safety and that the building's ability to achieve the level of safety has been demonstrated by

qualified people using the correct methods applied to the correct data.

Verification Method. A computer model or other tool or method used to demonstrate that a proposed solution meets the fire safety goals for the applicable fire scenarios. The designer can use any type and number of acceptable verification methods to evaluate the effectiveness of the design.

PART II – PERFORMANCE-BASED FRAMEWORK

This section (Part II) provides a general framework to be used in engineered design and performance-based code development. NFPA Technical Committees need to address the concepts and processes discussed below, providing the designers and AHJ's with a point of reference when developing and approving performance-based designs. How the Technical Committees can present this information in their document is discussed in Part III.

Chapter 3 Overview of Performance Approach

3-1 Performance versus Prescriptive

3-1.1 General. Until recent years, the fire protection community relied upon codes and standards that were entirely or primarily prescriptive, in order to design buildings and systems. These documents primarily account for fire safety by prescribing specific requirements without indicating how these measures work to achieve a desired level of safety. Over the past several years, efforts have been made within the fire protection community to develop performance-based codes and standards which explicitly state their fire protection goals and define the desired or acceptable level of safety. These codes and standards further define the fire protection goals into specific objectives, which must be met in order for the building or system to comply with the code.

3-1.2 Prescriptive Codes and Standards. In the past, codes and standards almost exclusively followed a prescriptive format, in which the code or standard specified detailed means to achieve fire safety for a generic use or application.⁵ These prescribed means included the specification of particular construction types and materials, limiting building dimensions and travel distances, or specific fire protection systems. Some requirements had performance elements, such as the use of qualifying tests (e.g. one-hour fire door) rather than detailed prescriptions of materials and designs. But even these codes and standards did not indicate how these design and construction practices worked together to achieve a desired fire safety goal.

A common analogy to a prescriptive code is a cookbook, which outlines specific ingredients to be used, how these ingredients are to be cut and mixed, what the oven should be set at, what types of cookware should be used, and how the recipe should be served. Like a recipe in a cookbook, the

prescriptive codes have generally been developed and modified based upon previous successes and failures.

While these prescriptive documents are generally easy to use in typical designs and occupancies, they are a barrier to innovation. Prescriptive codes and standards do not allow the stakeholders and building users to determine the actual level of safety achieved in a building if that building design differs from those considered by the Technical Committee in the development of the document. Additionally, prescriptive documents do not provide a process or basis for revising the requirements to achieve the intent of the code or standard. For such complicated or innovative building designs, design teams are forced to attempt to demonstrate equivalency by undertaking a process similar to a performance-based design, only without the structure and documentation requirements covered in an actual performance-based code or standard.

3-1.3 Performance-Based Codes and Standards.

A performance-based code, standard, or similar document is one that specifically states its fire safety goals and desired level of safety, and then references approved methods which can be used to demonstrate a design's ability to meet these specified goals.⁶ Instead of specifying exact construction materials or protection systems to be used as in a prescriptive code, a performance-based code or standard allows the use of any and all solutions that demonstrate compliance with the stated goals. This system allows the stakeholders in a building design the flexibility to design new and innovative structures, while maintaining a specified level of safety.

3-1.4 Why Performance? Prescriptive codes and standards claim to establish only minimum requirements. However, these codes and standards do not provide a means to quantify an actual level of safety in the building design. This can lead to building designs with costly features that do not materially improve safety or, conversely, to code compliant designs that nevertheless miss a significant type of risk or hazard and fall short of a desired level of safety. Additionally, building designs frequently incorporate features not explicitly covered by prescriptive documents, and the safety consequences of these optional features, for good or ill, are unknown.

This leads design teams to explore the use of "equivalency," in which they attempt to demonstrate

that the design meets the intentions of the prescriptive document, which they must infer from their interpretation and understanding of the code and what is known of the background of its development. This new “equivalent” design must then be presented to the AHJ for his/her review, which will rely on that individual’s inferences and interpretations. The situation is rife with potential for confusion, frustration, and unresolvable disagreements. Nevertheless, this “equivalency” option has been in use for decades, without the help of an outline for the process of determining the intent of the code, developing and testing a design, and submitting the results to the AHJ.

By providing a new performance-based code or standard, or adding a performance-based option to an existing code or standard, a Technical Committee can clarify, improve, and facilitate the free-form equivalency qualification outlined above. If a design team believes that the prescriptive requirements for a particular building design are excessively redundant, a performance-based option in the code or standard would present to them the chance to develop a new and innovative design, which has a level of safety equal to or greater than that specified in the code at a lower cost to the building owner. Additionally, if the owner would like a defined level of safety higher than what he/she believes is provided by the prescriptive code or standard, then the design team can develop a performance-based design meeting his/her personnel requirements while also meeting the specified goals of the performance-based option.

Finally, the use of the “equivalency” option of the prescriptive documents allows, and often forces, the design team to determine the intent of the prescriptive code and societal goals regarding expected level of safety, before designing and evaluating the building or system. While this system will often lead to what one might describe as a performance-based design, it is completed without any guidance regarding what the specified goal and intent of the code actually is, what types of information should be used to design the buildings and verify its performance during various fire scenarios, or how this information should be compiled into a submittal to the AHJ. These, and other related topics are typically covered in a performance-based code or standard, providing guidance to both the design team on the completion and submittal of performance-based designs, and to the AHJ regarding the types of information that

should be included and what level of performance should be expected.

3-1.5 Performance-Based Engineering and Performance-Based Codes.

The concepts of performance-based engineering and performance-based codes are inherently similar, yet far from identical.⁷ Performance-Based engineering involves working with stakeholders on a specific building, developing performance criteria and loss objectives for that particular building. Using the specific stakeholders’ intentions for the building and their desired level of risk to its inhabitants, the engineering design team will then develop trial designs to evaluate against the performance criteria, documenting each variable specific to that building along the way.⁸

Performance-Based codes and standards differ from performance-based engineering in that they will not be directly related to specific buildings or particular designs, and will consequently not incorporate the same level of detail regarding specific variables. More importantly, they will emphasize the intentions, risk preferences, and other values of the community, rather than those of a stakeholder team that is likely to put more emphasis on cost and other non-safety considerations.

Performance-Based codes and standards begin with code writers defining minimum levels of risk to which the building users are to be exposed. Technical Committees will have to develop fire safety goals and objectives based upon this level of risk that is acceptable to society. While these values specify a minimum level to which a building is to be designed as would be expected from a prescriptive code, the general framework of a performance-based code or standard provides design flexibility while maintaining a level of safety acceptable to society.

A performance-based code or standard should present a design framework, which can include information relating to fire scenarios, verification methods and design tools, occupant characteristics, etc. However, Technical Committees should avoid strict prescriptive requirements for the actual engineering unless necessary to ensure proper specification of the criteria for evaluating the design. This document, and any additional NFPA Performance-Based Primers, outlines a process for the development of performance-based codes and standards, which can then be used by a design team

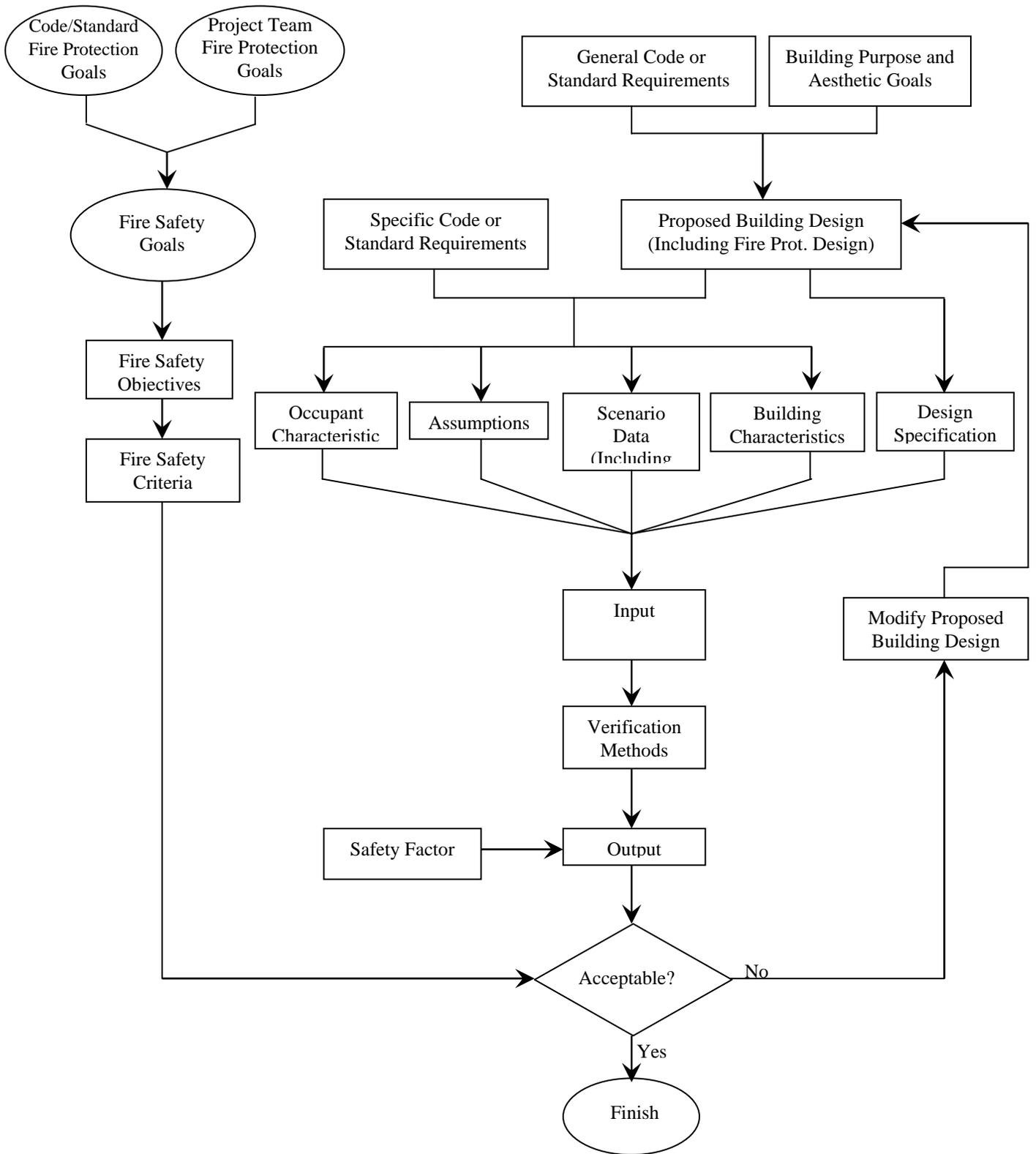
for performance-based engineering of a specific building or system.

3-2 Performance-Based Code and Standard Development.

3-2.1 General. In contrast to a prescriptive document, where the code or standard specifies required values and levels for each facet of the fire protection and building design and construction, a performance-based document requires the use of a process to come up with a building satisfying particularly fire safety goals reflecting or constrained by societal values.

3-2.2 Performance-Based Design Process. A Technical Committee developing a performance-based document or a performance-based option within a code or standard must outline a general procedure which can be followed by the design team to develop and document the building or system design. A performance-based code or standard may require particular values to be used in the design of the building or fire protection system, but it ultimately leaves the burden, and accompanying flexibility, of the design and evaluation to the engineer.

Figure 3-2.2 illustrates a performance-based process which is discussed and referenced throughout this primer. This flow chart shows that, while the Technical Committee can specify requirements for characteristics, assumptions, or scenario data, each of these components of the performance-based design is also going to be dependent on the particular proposed building design. Additionally, each of the five separate blocks (Occupant Characteristics, Assumptions, Scenario Data, Building Characteristics, and Design Specifications) should be constructed such that they can be combined to define a detailed fire scenario. The Technical Committee, and the design team, must recognize that, while this primer separated the input data for the fire scenarios into these five separate blocks, some of the information from an actual design might be related to two or more of the categories. In these cases, the information must be defined to a particular category as accurately as possible using engineering judgement.



*Figure 3-2.2 Performance-Based Design Process

3-2.3 Developing Performance-Based Provisions.

The development of a performance-based document or option within a code or standard is ultimately the responsibility of the Technical Committee. However, NFPA will provide support to any Technical Committee wishing to undertake this process. If a Technical Committee wishes to develop a performance-based option or stand alone document, they should notify the staff liaison, who will then pass this information on to the Performance-Based Support Team. At this time, each member of the Technical Committee will be sent a copy of the Performance-Based Primer(s) to review, which outline the performance-based process, terminology, and important concepts. After the Technical Committee has had an opportunity to review this information, a representative of the Performance-Based Support Team will attend a committee meeting, delivering a presentation regarding the development of performance-based documents, reviewing the concepts outlined in the primer(s), and discussing any important issues raised during the development of previous performance-based documents. This will give the Technical Committee a chance to ask any questions regarding the developmental process and any of the work involved in producing performance-based provisions.

If the Technical Committee wishes to continue with the development of a performance-based document, the representative of the support team will arrange a brainstorming session, which will address the development of goals, objectives, scenarios, and assumptions. This brainstorming session is intended to assist committee members in not thinking prescriptively, and should provide the Technical Committee with a foundation and core of a performance-based document, around which they can complete the development of the code or standard with minimal input from the support team. In addition, this brainstorming session will allow the support team to blend their knowledge of performance-based codes and standards, the concepts involved in their development, and any past problems encountered with previous performance-based documents, with the Technical Committee's expert knowledge of the document in question.

Figure 3-2.3 consists of a flowchart outlining the initial stages of development of a performance-based document. The first item addressed during the brainstorming session should be the development of the goals and objectives of the document. This will provide the scope around which the rest of the

performance-based provisions will be constructed. The goals of the document should relate to both the performance and prescriptive aspects of the code or standard, which will establish a basis for the equivalency option within the document. Following the development and acceptance of the goals and objectives, the Technical Committee should address either the performance criteria, characteristics and assumptions, or the fire scenarios, as there is no requirement for the order in which these items must be approached. The Technical Committees may specify exact criteria levels, or they may provide guidance which can be used by the design team to develop criteria specific to each building in question. The document must also include any requirements for the (building and occupant) characteristics and assumptions, as well as guidance which can be used by the design team to determine values and ranges for any characteristics and assumptions not specified by the document in question. The fire scenarios addressed and specified should highlight any unique issues covered by the particular document in question.

At this stage, the Technical Committee should be able to use the primer(s) to complete the development of the characteristics and assumptions, as well as the fire scenarios sections of the document. The Technical Committee should use the Primer(s) to select and specify proper design tools which can be used to verify the performance of the engineered design. Also included should be information relating to the acceptance of this design, incorporating information relating to uncertainty analysis and safety factors which may have to be included to account for any uncertainty in the design input and verification methods. Finally, the Technical Committee needs to specify a means to document the design, so that it can be properly reviewed by an approved Authority Having Jurisdiction.

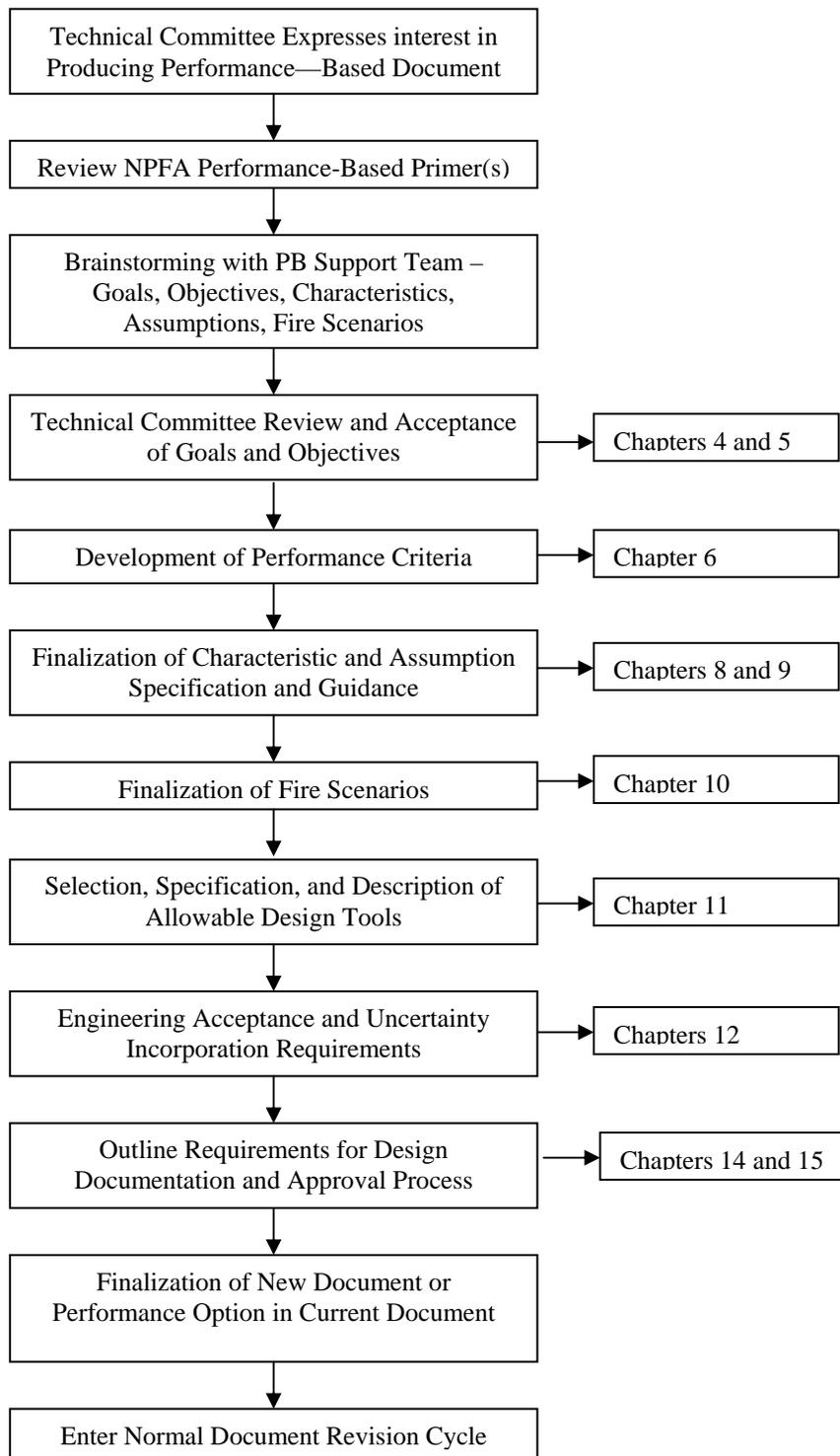


Figure 3-2.3. Performance-Based Document Development

3-3 Performance-Based Design Intentions.

3-3.1 General. The development and specification of goals and objectives is the first step that a Technical Committee should take when writing a performance-based code or standard. The specification of exact performance criteria based upon the specified objectives can be incorporated into the code or standard if desired by the Technical Committee, or it can be left to the design team to develop criteria levels based upon the objectives. In either case the criteria must be approved by the AHJ. Performance-Based goals, objectives, and criteria are covered in greater detail in PART III of this document.

3-3.2 Goals. The overall goal of any NFPA document is to simply reduce the burden of fire and other perils on quality of life. This overall goal may manifest itself differently in each code and standard, and the Technical Committees must refine it to best fit their particular document. The goal statement of a performance-based document should be stated as a broad, qualitative expression of the overall, primary concern of that particular document, focusing on impact on people, property, or the environment. Chapter 4 defines typical, broad categories of performance-based goals that can be applied in concept by the Technical Committee to a particular code or standard.

3-3.3 Objectives. After the Technical Committee defines a particular fire safety goal, objectives that provide a greater level of qualitative detail should be developed. These objectives define requirements of the building, the fire, or the occupants which must be achieved in order to satisfy a particular fire safety goal, and they will act as a link between the broad qualitative goals and specific, quantitative performance criteria. While the goals discussed in Chapter 4 can be applied to almost every NFPA document, objectives should be developed by the Technical Committee to reflect the nature and intent of the document in question.

3-3.4 Performance Criteria. After developing the objectives based upon the broad qualitative goals, these objectives must be further quantified into specific performance criteria, stated in directly measurable, engineering terms. It is against these specific performance criteria, which include but are not limited to values such as temperature, radiant heat flux, or levels of exposure to fire products, that the design output will be compared in order to

determine whether the design meets the performance provisions or must be further modified and re-evaluated. As the performance criteria are related to the physics of the fire or human physiology, they need not be document or scenario specific. The performance criteria can be specified in the code or standard or, if the Technical Committee desires, their development can be left to the design team using the specified objectives and the building in question. In either case, the levels are subject to the approval of the Authority Having Jurisdiction, and documentation regarding the reason for selection should be provided in the submittal to the AHJ.

3-4 Design Input and Verification

3-4.1 General. In addition to specifying goals, objectives, and possibly criteria, the Technical Committees will need to provide guidance on the development of input variables and the selection of verification methods. As shown in Figure 3-2.2 the input data will ultimately be developed from specific code and standard requirements specified by the Technical Committee, and from parameter and variable values developed by the design team based upon the proposed building design. The input values, specified by the code or standard or developed based upon the building design, for a performance-based design are typically separated into three components: Design Specifications, Characteristics and Assumptions, and Fire Scenario Data. The data from these three sources is compiled into a list of input for the verification methods chosen by the design team to evaluate the design.

3-4.2 Performance-Based Design Process. In order to prepare a performance-based code or standard, the Technical Committees must understand the basic process that will be used by the design team to prepare a design that satisfies the performance objectives and criteria outlined in the code or standard. Depending on the code or standard in question, the design team may specify criteria based upon the performance goals and objectives. They will then develop several trial designs for the building, taking into consideration the hazards and fire scenarios against which they are expected to provide protection. From each of these trial designs, the design team will compile a list of input variables to be used by the verification method chosen to evaluate the design.

NFPA 550, the Fire Safety Concepts Tree, provides a general approach which can be taken to meet the

code or standard fire safety objectives: prevent ignition; manage the fire impact; or manage the exposed.⁹ Each of these three branches of the overall tree framework is further divided to show the various avenues one can select to achieve each approach separately. These concepts, if referenced by the Technical Committee can provide the design team with a framework for developing performance criteria if they are not specified in the code or standard, as well as a basic design philosophy that can be applied to the building design in order to meet the performance objectives.

The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings, referred to as the SFPE design guide throughout the remainder of this document, outlines a detailed method for developing and evaluating performance-based designs.¹⁰ In this guide, the level of fire safety in a building is defined as a function of the interaction of each of the components of the fire protection system. The components discussed in the SFPE design guide include: Fire initiation and development; Spread, control, and management of smoke; Fire detection; Fire suppression; Occupant behavior and egress; and Passive fire protection. These components can be combined by the design team in the development of the performance-based design, with those components used dependent upon the performance criteria specified in the code or standard or developed by the design team. The design team should develop and evaluate various trial designs using different component combinations so that the safest, most economical design can be selected. When preparing the initial trial designs, the design team should take into consideration the hazards and fire scenarios to which the building is to be exposed, increasing the likelihood of the initial building design satisfying the performance criteria and decreasing the need and number of changes that will have to be made after the evaluation of the trial design is completed.

Each of these subsystems and components is elaborated on in Chapter 9 of the SFPE design guide. Technical Committees interested in incorporating performance-based wording into a code or standard should provide reference to this document and these concepts, as they will provide a basis for the development of performance-based designs, which can then be evaluated against the goals and objectives specified in the code or standard. Once the design team has developed the proposed building designs, they should determine the input variables

which will be used in the verification of these designs.

3.4.3 Design Specifications. Based upon the proposed building and fire safety system designs developed using the concepts described briefly in the previous paragraph, the design team will develop a list of design specifications that will have an impact on the fire safety analysis of the building. Examples of design specifications, which are discussed in greater detail in Chapter 7, include floor height and area, construction materials, and standpipe locations.

3.4.4 Characteristics and Assumptions. The characteristics and assumptions used in performance-based design relate to the building, the occupants of that building, the surrounding area, and any outside forces that might act upon that building during an emergency situation, but that are not included in the building design specifications. The characteristics are further separated into occupant and building characteristics. These topics are covered in greater detail in Chapters 8 and 9 of this document.

3.4.4.1 Occupant Characteristics. The characteristics of the occupants can be defined as any and all factors required to predict the behavior of the people in the building before and during a specific fire scenario, as well as the affects the fire and products of combustion will have on these people. The occupant characteristics are typically separated into four basic response characteristics (sensibility, reactivity, mobility, and susceptibility), each of which can be expressed as or translated into a component of time in the occupant egress time evaluation. The Technical Committee should avoid specifying these characteristics in terms of typical values, but should instead concentrate on setting a representative range of combinations of characteristics or focus on a particularly challenging combination of occupants, representing the worst case that society would expect to be protected. In addition to the range of occupant response characteristics, distributions of the occupants, including their number and locations, should be constrained or addressed by the code or standard.

3.4.4.2 Building Characteristics. The building characteristics can be defined as those features of the building that will have an impact on the overall design performance but are not included in the actual building design specifications. These can include such things as the anticipated layout and flammability characteristics of the building contents

and furnishing, as well as the flammability and burning characteristics of the interior finish materials.

3-4.4.3 Assumptions. Assumptions are defined as specifications that do not vary across fire scenarios and remain constant throughout the evaluation process. Some assumptions can be left to the design team, but the Technical Committee will typically require that certain assumptions be incorporated into the building design. Care should be taken to ensure that each assumption remains sensible and consistent across the various fire scenarios, and that these assumptions remain true throughout the analysis. Assumptions encompass areas such as retained prescriptive requirements and system performance, the applicability of fire models and design tools, ambient conditions in the building at the time of ignition, the performance of the fire department, the level of staff assistance, and the conditions of the doors and ventilation system.

3-4.5 Fire Scenarios. The fire scenarios, and scenario data generated from them, define the fire challenges that a building is expected to experience. The description of each scenario should include a detailed account of the conditions or factors related to any stage of fire development, such as ignition sources, configuration of fuel, and condition of supporting structure. The design fire is a component of each individual scenario developed from the verbal description of the initial and secondary fuels, the ignition sources, and other scenario information quantified into specified heat release rate curves, specific growth rates and other fire related properties. These design fires are simply a depiction of the fire and should not include information relating to outside forces which might act on the fire, such as building occupants or automatic suppression. It is these design fires, incorporated into the scenario data, that will actually be used as input for the verification methods.

A range of fire scenarios should be investigated, accounting directly, or by representation, for every possible fire from which society expects to be protected. Each possible, individual fire need not be investigated separately, as they can be lumped together into a series of scenarios which are either equivalent to or more severe than the fires represented. Additionally, some fires may be regarded as too unlikely and too severe for the building to be expected to handle, but that determination should not be left to the design team.

In the development of a performance-based code or standard, the Technical Committee may specify specific scenarios, and design fires, that must be used in the design evaluation. Additionally, the Technical Committee may specify certain aspects of a fire scenario to be used, leaving the design team to complete the scenario development based on site-specific building details, characteristics, and specifications. The Technical Committee should use these two methods to develop a range of fire scenarios that will ensure the fire safety performance of a building meets societal goals and objects. Additional details on fire scenarios are included in Chapter 10.

3-4.6 Verification. Once the design team has compiled a complete list of input based on the code requirements and proposed building design, they must verify that this design meets the fire safety goals and objectives quantified by the performance criteria. This process begins by selecting a design tool whose output can be directly compared to the performance criteria, and which will use as many as possible, if not all, of the input compiled from the design specifications, characteristics, assumptions, and fire scenarios. A more detailed description of the various types of design tools available is provided in Chapter 11.

Proper verification of a design's performance will be directly related to the design team's selection of appropriate verification methods. The Technical Committee should include language in the document to ensure that the design team is aware of the various types of verification methods permissible for use by the document. Verification methods typically consist of one of the following: deterministic tools based on mathematical equations that describe physical phenomena; probabilistic tools typically based in part or entirely on fire loss data; heuristic tools based on investigation, problem solving, experience, and especially engineering judgement; or laboratory tests, which can be used to verify either a system component's or a whole room's performance.

Deterministic tools are further separated into hand calculations that can be solved using nothing more than a calculator, computer-based physics models used to model the effects of a specified fire, and evacuation models used to simulate the behavior and movement of people during a fire situation. Both the physics and the evacuation models can be further classified by the level of complexity and modeling capability. Additionally, there are various types and

sizes of tests that can be run, depending on what the design team hopes to learn or verify. It is up to the design team, with the approval of the AHJ, to select the verification method appropriate to the level of complexity of building in question.

The Technical Committee should provide information relating to each type of verification method whose use is permitted by the code or standard, as well as the limitations of each. Chapter 11 includes an elaboration of this information and that provided in the previous paragraphs, as well as various sources for the acquisition and review of both fire and evacuation models.

3-5 Design Acceptance and Approval

3-5.1 Design Team Acceptance. The design team should use an appropriate verification method to produce design output which can be compared to the performance criteria. This output will have a level of uncertainty associated with it, due to multiple types of uncertainty inherent in the design process. The design team should evaluate the level of this uncertainty using techniques such as sensitivity analysis. In addition, before comparing the design output to the performance criteria, the design team should apply an appropriate safety factor. If, after the application of the safety factor, the design output satisfies the performance criteria, then the design can be labeled as acceptable, and the performance-based design process can continue. Additional information on the application of uncertainty analysis and safety factors, as well as design acceptance, is included in Chapter 12.

3-5.2 AHJ Approval. After the design team has developed a design which satisfies the performance criteria as discussed briefly in Section 3-5.1, the design should be documented as required by the Technical Committee in the code or standard. The specification of appropriate levels of documentation is discussed in greater detail in Chapter 14. The design team should present the AHJ with a submittal, which includes a Design Report, Specification and Drawings, and an Operations and Maintenance Manual. It is then the obligation of the AHJ to review this submittal, and either approve the design as is or request further verification. This approval process is discussed in more detail in Chapter 15.

PART III – PERFORMANCE-BASED DESIGN INTENTIONS

This section (PART III) discusses the development and specification of goals, objectives, and criteria for performance-based documents. NFPA Technical Committees wishing to incorporate performance-based language into their code or standard must develop basic goals and objectives of that document. Depending on the document in question, the Technical Committee may also develop specific performance criteria, or may leave these to be developed by the design team.

Chapter 4 Goals

4-1 General. The goal statement of a performance-based document should be a broad, qualitative expression of the overall, primary concern of the document. Goals should be stated in terms that are potentially measurable, even if the precise measurement scale is not specified. Thus, goals may be stated in terms of impact on people, property or the environment, business interruption, or any combination of these. Goals should address the primary concern of the document.

4-2 Definition. Given the nature of a performance-based approach (i.e., flexible), the definition of terms becomes an important issue. Therefore, an authoritative definition of “goal” is presented, followed by the term’s envisioned use in NFPA documents.

4-2.1 Dictionary Definition. A standard definition of a goal is “The purpose toward which effort is directed, an objective.”¹¹ Alternatively, this could be stated as that which one plans to do or achieve. A goal may suggest an idealistic or even a remote purpose.

4-2.2 NFPA Context. Given NFPA’s mission, the (single) goal of any NFPA performance-based provision is readily evident: to reduce the burden of fire on the quality of life. As discussed further in this document, this goal may be manifested in different ways, depending on the particular NFPA document being considered. Goals do not rely on assumptions. For example, “avoidance of flashover” would not be a goal because it relies on assumptions about what kinds of fires cause harm and how flashover is defined.

4-3 Performance-Based Fire Safety Goals.

Typically, fire safety goals fall into six broad categories (“occupancy” examples shown in parentheses):

- (a) Life safety of occupants (theater);
- (b) Property protection (warehouse);
- (c) Mission continuity (shipboard engine room);
- (d) Environmental consequences (outdoor rubber tire storage);
- (e) Heritage preservation (museum gallery); and
- (f) Firefighter safety (all of the above “occupancies”).

4-3.1* Life Safety. Goals relating to life safety are the most common and arguably the most important in fire and other emergency situations. The public places trust in the built environment (i.e., in anyone involved in constructing buildings, structures, and other facilities: designers, engineers, code officials, etc.) to maintain some level of safety or protection from adverse conditions. Therefore, maintaining the health, safety and welfare of building occupants could be a goal.

4-3.2* Property Protection. Property protection considers the impact of fire on the structural elements of, as well as the equipment and contents in, a building.¹² While the natural measurement scale for this goal would seem to be monetary, available models rarely suffice to predict monetary losses. Instead, they can predict areas and volumes affected by type of damage (e.g., flames, smoke). Thus, the goal of reducing the impact of a fire both within and outside of a building falls into the general category of property protection; e.g., limiting the spread of a fire. There are many issues with regard to limiting the spread and effects of fire. On a macro scale, building design should be such that a fire will not spread from one building to another. While within the building, it is desirable to limit the spread of fire before it can reach specific areas of the building, e.g., areas of refuge or other places of safety.

4-3.3* Mission Continuity. The goal of mission continuity is analogous to that of property protection. However, instead of considering the physical nature of a structure, mission continuity is more concerned with the ability of a structure to perform its intended function(s) and how that affects the structure’s tenants. Business interruption is perhaps the best known example of a mission continuity loss and is also something described as “indirect loss,” as contrasted with “direct loss” from damage to

structure or contents. Obviously, the building must remain structurally sound for a required period of time for this to happen, so there is a link between property protection and mission continuity. But mission continuity is intended to protect an organization's ongoing mission, production, or operating capability.¹³ Thus, property protection and mission continuity are not mutually exclusive.

4-3.4* Environmental Consequences. The goal of limiting the impact of a fire on the environment may be trivially easy to achieve for most fires, even some large fires, but it is a distinct goal of increasing importance to nations around the world. Air pollution in the form of the smoke released during a fire is probably the most recognizable form of damage to the environment from a fire. However, the run-off from manual fire suppression operations and/or sprinkler system discharge may also damage the environment, (e.g., when non-water soluble, toxic chemicals are involved in some way).

4-3.5* Heritage Preservation. Heritage preservation is meant to keep historical and cultural "items" from harm. Items in this case are usually one-of-a-kind and could be an entire building, archaeological and other historical artifacts, works of art, manuscripts, etc. One aspect of heritage preservation is protecting items in museums. If these items are destroyed, their loss to our society and culture may be impossible to measure. In some cases, heritage preservation is similar to property protection except any resulting fire damage should be less extensive than for property protection.

4-3.6* Firefighter Safety. Typically, firefighters are not considered to be occupants of a building and therefore are not usually the subject of the life safety goal of 4-3.1. Part of the reason for this approach is that firefighting is inherently dangerous and risks associated with the job cannot be entirely eliminated. However, there are goals which, if achieved, give firefighters a reasonable chance of achieving manual extinguishment without undue threat (i.e., with minimal risk). For example, the fire department requires access to the building itself and to specific areas within the building, such as parking lots and stairwells. Furthermore, maintaining the structural integrity of the building is also important to ensure firefighter life safety. Thus, the effectiveness of firefighters is a direct result of their safety.

4-4 Development of Fire Safety Goals. As discussed in Section 3-2.3, if a Technical Committee

wishes to produce a performance-based document then a representative of the Performance-Based Support Team will arrange a brainstorming session. The first thing this brainstorming session should accomplish should be the development of fire safety goals for the document. Typically, the goal statement of a particular document will consist of one or more of the items discussed in the previous section. The goals can be listed in a separate, stand-alone section of the code or standard or can be included in the "Document Purpose" or "Document Scope" section of the code or standard.

Chapter 5 Objectives

5-1 General. The fire safety objectives of performance-based codes and standards are intended to be more specific than goals. In the context of performance-based provisions, objectives provide a greater level of (qualitative) detail than goals. Objectives are stated in more specific terms than goals and are measured on a more quantitative rather than qualitative basis. Objectives are the link between fire safety goals and performance criteria. In general, objectives define a series of actions necessary to make the achievement of a goal much more likely.

5-2 Definition. Given the nature of a performance-based approach (i.e., flexible), the definition of terms becomes an important issue. Therefore, an authoritative definition of “objective” is presented, followed by the term’s envisioned use in NFPA documents.

5-2.1 Dictionary Definition. An objective is “something worked toward or striven for; a goal.”¹⁴ An objective often implies that the end or goal can be achieved.

5-2.2 NFPA Context. The NFPA in-house task group defined an objective as a requirement of the fire, building, or occupants which needs to be obtained in order to achieve a fire safety goal.¹⁵ Objectives are stated in more specific terms than goals and tend to be more quantitative rather than qualitative.

5-3 Difference Between Goals and Objectives. The primary difference between fire safety goals and objectives is that objectives are more specific to the problem being solved or the document being developed. The same goals may be applied to most NFPA documents, while objectives are intended to reflect the nature and intent of the document in question. For example, the goal of maintaining life safety can be used for a document dealing with smoke management systems as easily as it can be used for one dealing with an active suppression system. However, the objectives of those two documents would not be the same. Therefore, the objectives for these two documents would discuss, in quantitative terms, how life safety may be maintained by using either a smoke management system or an active suppression system. The objectives of the individual documents must be different since they are dealing with markedly different systems,

components, and occupant responses. Finally, goals are always qualitative, while objectives may also be quantitative.

5-4* Performance-Based Fire Safety Objectives. Since objectives are document specific, it is difficult, but not impossible, to provide general fire safety objectives. The NFPA in-house task group report provided some general fire safety objectives:¹⁶

- (a) Prevention of structural damage;
- (b) No life loss in the room of fire origin;
- (c) Separating occupants from fire effects for “a specified period of time;” and
- (d) Containing the fire to the room of origin.

The third example helps illustrate how similar objectives may be different for different documents. Depending on the scenarios of interest, the specified time could be several minutes (e.g., patient room in a health care facility) to several hours (e.g., non-fire floor in a high-rise building).

5-5 Development of Fire Safety Objectives. Fire Safety objectives must be developed separately for each individual code or standard as they are more specific to the documents general intent than fire safety goals. Following the determination of the fire safety goals, the Technical Committee and Performance-Based Support Team should develop fire safety objectives which are based upon the document goals, but provide additional detail, and may be stated in a more quantitative manner. These objectives should be stated in a separate section within the document, along with text stating that if each objective is obtained by the building, then that building can be said to meet the fire safety goals.

Chapter 6 Performance Criteria

6-1 General. Performance criteria tend to be the most specific parts of performance-based documents. Criteria can be thought of as quantified objectives, which state in engineering terms the required level of performance of the building.

6-2 Definition. Given the nature of a performance-based approach (i.e., flexible), the definition of terms becomes an important issue. Therefore, an authoritative definition of “criterion” is presented, followed by the term’s envisioned use in NFPA documents.

6-2.1 Dictionary Definition. Criterion is defined as “A standard, rule, or test on which a judgment or decision can be based; criteria (pl).”¹⁷

6-2.2 NFPA Context. In relation to NFPA documents, criteria are defined as performance objectives (emphasis added) for individual products, systems, assemblies, or areas, which are further quantified and stated in engineering terms.”¹⁸ Examples include temperature, radiant heat flux, and levels of exposure to fire products. In this sense they are directly “measurable” (i.e., by experimentation, analysis and/or calculation) values and levels that, if achieved, result in attaining the specified fire safety objectives and consequently achieving the associated goals.

6-3 Performance-Based Fire Safety Criteria.

6-3.1* Performance Criteria Specification. Depending on the code or standard in question, performance criteria may or may not be document specific. Performance criteria are typically related to the physics of fire and the human physiology of its consequences. As such, criteria can be applied to more than one document or scenario. Candidate examples of fire safety criteria are:

- (a) Limiting a structural steel member to less than 540°C;
- (b) Limiting COHb levels to less than 25%;
- (c) Limiting upper layer temperatures to less than 500°C above ambient;
- (d) Limiting radiant flux at the floor to less than 20 kW/m².

6-3.2 Performance Criteria Levels The Technical Committee must ensure that they select the proper level of detail for performance criteria. If the criteria

are stated too specifically, they may oversimplify the phenomenon of fire and its effects, leading to poor guidelines that do not reflect real performance. On the other hand, if they are stated too generally, they may provide insufficient guidance to a user on how to evaluate designs.

6-3.3 Performance Criteria Development A collection of test methods, each with a pass/fail threshold, might appear to provide a set of performance criteria. However, appropriate performance criteria must quantify the higher-level goals and objectives without inappropriate assumptions about which fires matter and how fire effects occur. Few, if any, test methods can be used in isolation, without analysis for this purpose.

6-4 Development of Performance Criteria. Performance criteria can be specified in a code or standard, or it can be left to the design team to select and develop criteria based upon the specified objectives. This decision to include performance criteria in the code or standard is left to the Technical Committee. However, in either case, the levels are subject to the approval of the AHJ.

If the Technical Committee decides to include the performance criteria in the code or standard, they shall consist of the performance objectives, further quantified such that they can be stated in engineering terms. The criteria must be stated in terms directly comparable to the design evaluation output, and the Technical Committee should use values and levels appropriate to satisfy the fire safety goals, based upon the physics of fire and human physiology and capabilities. If the development of criteria is to be left to the design team, then similar concepts should be applied. The Technical Committee should provide guidance and appropriate sources of information which can be used to aid in the development of performance criteria, such as the SFPE design guide. Additionally, the Technical Committee should clearly state that any criteria specified by the document or the design team are subject to the approval of the AHJ, and should stress that the design team involve the AHJ early in the process to ensure that proper, conservative values and levels are used.

PART IV – PERFORMANCE-BASED INPUT AND VERIFICATION

be identified and the design team should investigate the consequence of this omission.

Chapter 7 Design Specifications in Performance-Based Design

7.1 General. Design specifications need to be compiled so that they can be used as input for the verification methods in order to evaluate the design against performance goals, objectives, and criteria. The design specifications specified as input should include any information relating to the design that may impact that building's performance during any of the fire scenarios.

7-2 Definition. The design specifications are those aspects of the building design that will have an impact on the fire safety analysis. These design specifications should be expressed in engineering terms, allowing them to be used as input in the analysis.

7.3 Building Design Specifications. Depending on the code or standard in question and the type of evaluation being completed, various input values based upon the architectural and structural design of the building may be required. The design team should develop a detailed list of each of the values that will be used as input for the fire safety evaluation. Possible building design specifications may include building height, stair locations, floor area, etc.

7.4 Fire Protection Design Specifications. In addition to the various input values which can be taken from the building design, information relating to the system designed to prevent or provide protection from fire should also be compiled into usable input parameters. The actual system design can be completed using guidance from the SFPE design guide. Possible fire protection system input values, such as the spacing and design density of a sprinkler system or the volumetric exhaust rate of a smoke control system, should be listed for each system designed into the building. Fire protection system input values may include both active and passive systems.

7.5 Design Specification Documentation. Each aspect of the design specification used in the analysis should be documented by the design team, and provided to the AHJ in a clear and concise manner for review. In addition, design specifications of the building that are not explicitly used as input should

Chapter 8 Development of Characteristics for Performance-Based Design

8.1 General. Characteristics are used in conjunction with assumptions, fire scenario data, and design specifications as input for the verification methods in order to evaluate the design against performance criteria. The characteristics are generally separated into building and occupant characteristics for the purpose of clearly expressing the design input. The Technical Committee can specify minimum values for the occupant or building characteristics; however, they must realize that some of the characteristics are going to be bound by the specific building in question.

8-1.1 Definitions. When referring to characteristics throughout this document the following definitions will be used:

8-1.1.1 Dictionary Definition. *The American Heritage College Dictionary* defines "characteristic" as "a feature which helps distinguish a person or thing."¹⁹

8-1.1.2 NFPA Context. In this context "characteristics" are those attributes of the building, the furnishings, and the occupants that need to be quantified and specified to permit evaluation of a design against specified goals, objectives, and criteria, using appropriate design fire scenarios and verification methods (Discussed in detail in Chapters 10 and 11). Basic examples of characteristics to be used in Performance-Based design include the physical and mental capabilities of the occupants or the flammability of the interior finishing materials.

8-1.2 Characteristics Role. Figure 3-2.2 depicts the role of characteristics as part of the evaluation of a proposed building design against specified fire safety goals, objectives, and criteria. They are separated into building and occupant characteristics, with both of these blocks of data used as input for the verification method used in the design. The building and the occupant characteristics are developed from a combination of specific code or standard requirements and attributes of the proposed building design.

8-1.3* Code or Standard Versus Designer Specified Characteristics. The Technical Committee must separate the characteristics into those specified or constrained by the code or standard, those required by the AHJ, and those

specified or chosen by the designer either in the design proposal or elsewhere in the analysis. Some building and occupant characteristics can be specified or constrained by the code or standard or by the AHJ as expressions of the community's judgements on acceptable risk. Conversely, the intended use of the building and the basic design specifications for building geometry and construction materials will be translatable by the design team into occupant and building characteristics. These characteristics will be part of a proposal to the AHJ, requiring his/her approval, but remaining the choice of the designer. It is very important that the Technical Committee realize that any values or attributes not specified or constrained by the code or standard are left to the interpretation of the design team, and consequently subject to the possibility of abuse. To prevent this potential abuse, the Technical Committee could seek appropriate values and references for occupant and building characteristics, which can then be implemented into or referenced by the code or standard.

8-1.4* Characteristics Development. For those characteristics not specified by the document or the AHJ, the design team will naturally be guided by the anticipated use of the building under consideration when selecting occupant and building characteristics. Additionally, the design team may have to select values for characteristics which are neither covered by the code or standard nor derived from the design (i.e. walking speed of an average person), in which case they should be realistic and conservative in their selection, reflecting the best available data.

The design team may be inclined to use "typical" values for the characteristics they are developing; however, the code or standard should be written to ensure the building is designed for the entire range of occupant loading and building stresses that can reasonably be expected to occur during the life of the building, and not simply the ideal case. To ensure proper conservatism, the Technical Committee may wish to specify minimum possible values for these characteristics, or they may reference publications, for use by the designer and the AHJ, which provide acceptable, conservative values for the occupant or building characteristics. Additionally, the Technical Committee will typically have to set requirements for the documentation and substantiation of this group of characteristics, as opposed to specifying exact values.

8-1.5 Characteristics Documentation. The language of the code or standard being developed by

the Technical Committee should provide requirements and guidance regarding which characteristics are to be documented in this section and which will be specified with the building design specifications. Additionally, the Technical Committee will also have to outline which of these characteristics are to be reflected in the analysis of design performance.

8-2 Occupant Characteristics.

8-2.1 Definition. The occupant characteristics can be defined as any and all factors required to predict the behavior of the people in the building before and during a specific fire scenario, as well as the effects of fire and the products of combustion on these people. The occupant characteristics used in the performance design should be based upon the anticipated distribution of people whom the design team feels will occupy the building or space being considered before and during the fire scenario. The occupant characteristics should not be set by the Technical Committee in terms of typical values, but in terms of either a representative range of characteristic combinations, or a particularly challenging combination consisting of the most difficult group of occupants that might occupy the building at one time and that society would expect to be protected.

8-2.2 Purpose. The occupant characteristics will be used as input for the design tools or verification methods when evaluating the building. Each occupant characteristic must be clearly identified and listed for the AHJ, and should be presented in a form which will allow use with the design tools selected to analyze the building. Those characteristics of the occupants identified by the design team but not used as input for the verification methods should also be presented to the AHJ for review.

8-2.3* Response. The primary occupant characteristics used during the design can be summarized in four basic response characteristics; sensibility, reactivity, mobility, and susceptibility.²⁰ Each of these response characteristics may be expressed as, or translated into a component of time in the occupants' required safe egress time.

8-2.3.1 Sensibility. Sensibility refers to the building occupants' ability to sense physical cues. Examples include the ability to sense, discern, and discriminate between audible, visual, and olfactory cues emanating from the fire, an alarm system, or some

other notification mechanism. This concept affects the occupants' time to detection or awareness of the fire.

8-2.3.2 Reactivity. Reactivity refers to the occupants' ability to correctly interpret the sensed cues and take appropriate action. The reactivity may be a function of the occupants' cognitive capacity, speed of instinctive reaction, or group sociology and dynamics. The Technical Committee may need to consider the occupants' anticipated familiarity with the building and premises, as this may influence how they react to an alarm or emergency. This concept affects the time from occupant detection to commencement of action or evacuation.

8-2.3.3 Mobility. Mobility refers to the building occupants' speed and overall ability to move. In addition to the occupants' individual characteristics such as overall health and stamina, the Technical Committee should also consider potential crowding phenomena, such as that which occurs at stairs and doorways. An occupant's mobility affects his/her required time for evacuation.

8-2.3.4 Susceptibility. Susceptibility refers to the vulnerability of the building occupants to the products of combustion. This susceptibility can vary depending on the occupants' metabolism, lung capacity, pulmonary disease, allergies, or other physical limitations that may affect the survivability in a fire environment. The sensitivity of the occupants affects the time to incapacitation or injury from fire products of combustion. The susceptibility of important equipment or processes can also be listed these characteristics, if protecting these items is amongst the fire safety goals and objectives.

8-2.4 Distribution. The entire distribution of occupants at the onset of fire should be included, unless the design is conservatively evaluated as a failure if fire or any products of combustion ever reach a potentially occupied space. This general breakdown may or may not be varied for each fire scenario investigated, as long as a conservative distribution is used for each. Regardless, the reasoning for the specified distribution in each scenario should be documented by the designer.

8-2.4.1 Location. The location of the building occupants at the beginning of the fire scenario is critical to the evaluation of egress paths and distances. A conservative approach that the Technical Committee can require or recommend is

that in every normally occupied room there be at least one person located at the most remote point.

8-2.4.2 Number. The number of occupants situated in the various locations should generally be based upon the maximum number of people that each occupied area is expected to or, conservatively, can contain at any time during the building use. It may not be realistic or conservative to assume that occupancy limits on rooms or facilities will be strictly enforced. The Technical Committee should be careful to not automatically select the maximum number of occupants as the worst case. An example of when the maximum number of occupants is not the worst case would be an industrial facility relying upon staff response to deal with an incident or fire scenario.

8-3 Building Characteristics.

8-3.1* Definition. The building characteristics are those features which are not part of the overall building design, but will have an impact on the building's performance. The building's performance may also have to be evaluated based upon its ability to protect important areas or processes located within, and in these cases the characteristics of these areas should be specified by the design team.

8-3.2 Purpose. The characteristics of the building will be used as input when evaluating the building. Each specification and characteristic, expressed as quantitative parameters, variables, and other values which can be used in engineering calculations and test specifications, should be listed by the design team for review by the AHJ. Those characteristics of the building identified by the design team but not used as input for the verification methods should also be presented to the AHJ for review. The Technical Committee can require that the AHJ receive the documentation and approve the characteristics designated as part of a pre-approval of the proposed design.

8-3.3* Building Contents. Building contents and furnishings are not normally specified in, or controlled by, the design specifications. However, they will have an impact on the fire and smoke spread and/or occupant behavior. The Technical Committee can require that the design team present the AHJ with a description of the expected fuel packages located in the area of fire origin in each fire scenario. Additionally, the Technical Committee can include requirements for maximum permissible limits

on the flammability of furnishings and building contents. The Technical Committee can also specify particular fuel sources and configurations based upon the desired scenario data; however, there are some anticipated fire scenarios which will involve fuel sources and packages chosen by the owner and designer based upon the intended use of the building. A sensitivity analysis should be performed to determine the acceptable level of variation in the fuel characteristics and configuration, as outlined in Section 12-3.2.

8-3.4 Building Layout. The overall layout of the building needs to be clearly expressed by the design team. This information can often be included with the design assumptions and design specifications. Included with this section should be information not always shown on building plans, such as expected cubicle layout, temporary storage areas, and anticipated office arrangement. A sensitivity analysis should be performed to accurately determine the impact of these characteristics/assumptions, and how much these arrangements can be modified without a re-evaluation of that area or the building. This concept of "management of change" is critical in performance-based design, and is discussed in greater detail in Section 15-4.

8-4 Documentation.

8-4.1 Purpose. It is extremely important that the design team document the characteristics of the building, the occupants, and the fuel packages that are being used in each scenario. The Technical Committee should stress that the documentation will benefit the designer, the AHJ, and any design team which has to work on the building in the future. All components of the design that are not variable across scenarios can be listed as assumptions. All of the relevant characteristics need to be identified, documented, converted into input and submitted to the AHJ in an organized fashion. Even that information that cannot be used as input in the design and converted to output should be identified, allowing the AHJ to clearly outline the characteristics of the fuel for each scenario, the reason for selecting this fuel, the area of origin characteristics and the reasoning behind them, the building design characteristics, and the occupant characteristics. In addition, the source of all of this information should be included, allowing for quick and easy reviewing of the values and variables used. Some of the information and characteristics may be repetitive, and

the design team should make an effort to present the data in as clear a manner as possible to the AHJ.

8-4.2 Review. The AHJ shall review the characteristics for each component of the input outlined above, and he/she will have final approval on whether or not those characteristics are appropriate in the final design.

Chapter 9 Assumptions

9-1 General. Typically, the design team will have to make several assumptions regarding the building and its state at the time of the fire in order to evaluate its performance. The Technical Committee can specify minimum or maximum levels of these values, or it can be left to the design team to determine appropriate input values for each assumption. In either case, the actual values used must be approved by the AHJ.

9-2 Role of Assumptions. Assumptions are specifications that do not vary across scenarios and are not permitted to vary in the building design. If the assumption must be varied for a particular scenario, then it is no longer defined as an assumption, instead becoming part of that specific scenario. Examples of assumptions include the arrival time of the fire department or the availability of staff assistance in a hospital or similar building. Figure 3-2.2 depicts the role of assumptions in the building design process.

9-3 Assumption Consistency. The assumptions made by the design team during the design analysis must remain the same throughout the analysis, and can include any input values which do not vary from one fire case to another. The Technical Committee can require particular assumptions be made during the analysis. Any assumptions made by the design team must be sensible and mutually consistent across the various fire scenarios, and must remain true throughout the analysis. One example of this is that the analysis can not assume that a door remains closed throughout the analysis, while also allowing this door to be used as a means of egress for the people in the building.

9-4 Assumption Regarding Prescriptive Requirements. Assumptions regarding prescriptive requirements from the code or standard being modified by the Technical Committee, or a related code and standard which will impact the building performance, must be clearly stated along with a reference to the section of the code or standard from which the information was taken and how it relates. It may be appropriate to retain a prescriptive requirement if the evaluation analysis cannot be structured to adequately assess the feature (e.g., a sprinkler system needs control valves). However, Technical Committees should resist the temptation to retain a requirement solely because they cannot

imagine how a design could be safe without that piece.

9-5 Design Assumptions. Each of the following design assumptions should be addressed by the Technical Committee, if applicable. This section does not list every possible design assumption, and the Technical Committee should address requirements for any additional design assumptions that they feel are applicable to their document.

9-5.1* Emergency Response. Any attributes or other conditions related to the availability and response of emergency personnel shall be included in the Assumptions section of the submittal to the AHJ.

9-5.2* Staff Assistance. Any assumption made by the design team regarding staff assistance should be included in the submittal to the AHJ. In facilities that warrant such consideration, the Technical Committee may require that staff assistance be provided in sufficient numbers at all times to aid the building occupants in exiting the building in the event of an emergency.

9-5.3* Off-site Conditions. If the Technical Committee anticipates the need, they can require that off-site conditions that will directly or indirectly affect the ability of the building to meet the goals and objectives for any reason be specified or characterized sufficiently to evaluate the design. These assumptions would then have to be included in the submittal to the AHJ.

9-5.4 Model Applicability & Input. The designer must make assumptions regarding the applicability of the design tools and models that he/she will be using. These assumptions must be outlined for the AHJ, along with the reasoning used to select that particular verification method.

Chapter 11 describes the process of selecting the proper design tool for the analysis. Each of these design tools requires various input parameters in order to calculate the desired output to compare to the performance criteria. The input parameters not specified with the building or occupant characteristics, or design specifications should be included with the assumptions. These assumptions must remain the same throughout the analysis. Examples include ambient temperature, pressure, time to occupant response following an alarm (assumption based upon occupant response characteristics supported by reference material or test

data, and approved by AHJ), etc. The Technical Committee may specify those values and parameters imperative to that committee's goals, or they can rely upon the designer to make every relevant assumption, with final approval from the AHJ. In addition, any assumptions not used in the design tool or model and not converted to output must also be specified for the AHJ.

9-5.5 Ventilation. The state of the ventilation in the building must be assumed and documented before the fire scenarios are investigated by the designer. Like all of the assumptions, the ventilation conditions shall be the same for each fire scenario, unless the ventilation equipment is actively a part of one or more of the scenarios.

9-5.6 Doors. The state of the doors within the facility is important, particularly with regard to fire and smoke spread. The state of each door which would, if deployed, serve as a barrier to fire products of combustion or have an effect on ventilation, should be documented by the designer and presented to the AHJ. Once again, these assumptions must be consistent throughout the design.

9-6* Building Features and System Performance. The Technical Committee should specify how the building features and systems are to be designed and installed by referring to applicable NFPA codes, standards, and other appropriate documents for those components. The Technical Committee should also specify a level of performance (i.e., performance criteria) expected from the system following installation.

9-7 Assumption Documentation. Each assumption made by the design team before or during the analysis of the building should be documented for the AHJ. Any reference used to select value for these assumptions should be included. Additionally, the values for assumptions taken from the code or standard shall be duly noted. The assumption values used in the evaluation shall be documented under a separate heading, allowing the AHJ to easily determine if any of these assumptions were violated during any of the design and verification procedures.

Chapter 10 Fire Scenarios in Performance-Based Design

10-1 General. Fire scenarios define the fire challenges a building is expected to mitigate. Therefore, every imaginable fire must be either (a) addressed by a fire scenario that is explicitly defined, (b) presumed to be manageable because a similar or more severe scenario has been explicitly addressed, or (c) regarded as too unlikely and too severe for the building to be expected to handle. Figure 3-2.2 illustrates the performance-based process, including the use of scenario data as input to the verification method. The overall fire scenario is a combination of the input values taken from the Occupant and Building Characteristics, the Assumptions, the Scenario Data, and the Design Specifications.

10-2 Definition. A fire scenario is a detailed description of the conditions or factors related to any stage of fire development critical to the outcome of the fire such as ignition sources, nature and configuration of the fuel, ventilation characteristics and location of the occupants, condition of the supporting structure, applicable operating equipment (e.g., reliability and/ or effectiveness). This allows the fire protection provisions of a building to be tested for their ability to achieve the fire safety goals, objectives, and criteria.

10-2.1. Using scenarios is a crucial step in performance-based design so it is important to be thorough and realistic when creating and selecting fire scenarios. "Realism" does not mean that only typical fires should be considered, because society expects buildings to achieve fire safety goals for nearly all fires the buildings might encounter during their lifetimes. "Thorough" does not mean that all scenarios must be explicitly addressed but rather that every fire must be either represented by a scenario that is addressed or explicitly excluded from consideration.

10-2.2. In practice, most of the outcomes regarding a scenario are either calculated using an appropriate calculation method or measured using a fire test. The scenario is defined by a small number of initial design specifications and assumptions, and the description of later steps, including consequences, is then the result of using computer modeling, other calculation methods, or tests.

10-2.3. Performance analysis based on risk requires calculation of probabilities of scenarios. A very

detailed scenario represents only a small probability of occurrence. This suggests that many scenarios would need to be evaluated to achieve completeness. To avoid such unworkable situations, the design team may use the approach of selecting very detailed scenarios to set up modeling or testing, and then use less detailed scenarios (which are, therefore, groups or sets of more detailed scenarios) to calculate probabilities.²¹

10-3 Design Fire. A design fire is a component of the scenarios, consisting of the detailed description of the fire but excluding conditions or factors regarding the building occupants and other factors that may impact fire development and/or severity. The design fire is the physical description of the fire including crucial information such as the fire's size, growth rate, heat release rate and other related fire properties.

The Technical Committee will generically describe the desired design fires for the scenarios it specifies (e.g., slow, medium, fast, ultrafast fire) including peak rate and duration, and decay time. The design fire parameters in each scenario must be approved by the AHJ to insure they reasonably portray the fire the scenario is describing.

If the design team's design fails a scenario, the parameters of the design fire should not be changed to a less severe fire in order for the design to pass.

10-4* Consistency. An important step in evaluating scenarios is to check that they are consistent with the other elements of the performance-based analysis. This is to say, the scenarios should not assume conditions that are incompatible with conditions assumed elsewhere in the analysis. For example, the spread of fire effects should not be calculated based on closed doors if the same doors are assumed to be opened repeatedly or continuously by evacuating occupants. If the scenarios are not consistent, either the scenarios or the other elements should be revised.

10-5 Scenario Application

10-5.1 Matching Scenario Specifications to Use of Scenario. It is important that the correct type of scenario is used. If the scenarios appropriate to one application are used for a different application, then the analysis may lead to false conclusions.

10-5.2 Scenario Selection for Design Analysis. Fire scenarios can be used to depict an array of

potential fire sources, rooms of origin, or other areas of special concern that may cause or contribute to a fire. In pre-fire situations, the building is most likely new, or at least new fire safety measures are being implemented. At this point, it is assumed that the room being considered has not experienced a fire; developing fire scenarios for that room is intended to provide a reasonable and credible challenge to the fire protection system. Applying scenarios in a pre-fire situation can be seen as a non-destructive test providing results that can be compared to the criteria and also as providing input into the verification methods.

10-5.2.1 Scenario Selection for Hazard Analysis. In performance-based design using hazard analysis, the key fire scenarios are limiting states. They represent the most severe fires for which the building design is expected to meet the fire safety goals and objectives.

In this approach a modest number of scenarios can be analyzed to establish the adequacy of the building relative to those scenarios and all less-severe fires.

10-5.2.2 Scenario Selection for Risk Analysis. In performance-based design using risk analysis, a large set of scenarios is needed, so that each scenario may be analyzed in terms of building design performance but also in terms of the probability that this or a similar scenario will occur. The set of scenarios must collectively address all possible fires, so the number of scenarios required will typically be larger than with hazard analysis.

10-5.2.3 Scenario Selection for Exploratory Analysis. The designer may select one or two high-probability, moderately challenging but not high-challenge scenarios to use in exploratory analysis that will indicate how the building design may typically work and how reasonably the modeling approaches and other performance-based analysis elements seem to work. It is important not to treat this exploratory analysis as sufficient for verification of the proposed solution.

10-5.3 Reconstructing of Actual Fire. Scenarios are also used after a fire has occurred, to reconstruct a fire. By developing scenarios based on theories of the fire's origin and testing them with verification methods, the theories can be scientifically narrowed down to only the most realistic and probable ones, to eventually determine the cause of the fire. Since in this situation the fire has already occurred, fewer

assumptions about the fire will need to be made. Also, there will be no need to include the wide variety of scenarios that are necessary in a pre-fire situation.

10-6 Scenario Selection

10-6.1* General. Many situations can occur throughout the life of a building. Some have a higher potential to occur than others. Others, though not typical, could be devastating in the event they happen. A good fire protection design should be able to achieve the fire safety goals and objectives for any typical or common fire scenario and for some of the less typical, potentially devastating fire scenarios, up to some level of acceptability that reflects the values of society. The central challenge in scenario selection is finding a manageable number of fire scenarios that are sufficiently diverse and representative so that, if the design is safe for those scenarios, then it should be safe for all scenarios, except for those specifically excluded as too unrealistically severe and too unlikely to be fair tests of the design.

10-6.2 Define Situation. Before selecting specific scenarios, the general type of scenario being used needs to be defined. It is important to have the characteristics and assumptions of the design in place because this information will help establish accurate scenarios. Refer to Section 10-5 for information on defining how the scenario will be applied.

10-6.3* Level of Acceptable Loss. The level of acceptable loss is expressed primarily in the criteria. The criteria are quantifiable measures of the goals and objectives. In performance-based design, it will be the project team who will determine the level of acceptable loss, subject to maximums set or implied in the performance-based code or standard. For example, owner's may state what they are willing to lose to fire (e.g., lives, property, business interruption). The designer quantifies the owner's expectations with criteria for the design to meet and the AHJ determines whether these criteria provide adequate safety required by society as defined by the applicable code or standard. The Technical Committee can also state the specific criteria in the code or standard, with these values subject to the approval of the AHJ. Statements of goals, objectives, and criteria placed in their document will define society's requirements for acceptable loss.

The choice of high-challenge scenarios required in the code or standard is another place where the Technical Committee can set limits on acceptable loss. When selecting scenarios, the Technical Committee should keep in mind that initiating fires more severe than the scenarios that the code or standard requires are, by that fact, deemed to be acceptable losses, based on presumed low probability. Considerable thought should go into drawing the line between fires which are deemed severe enough and likely enough to use in assessing a design and more severe fires deemed too unlikely to use in assessment.

10-6.4 Assumptions. When selecting scenarios, many assumptions will be made. The more complex the building, the more assumptions that will most likely be made. There is no limit to the number of assumptions that can be made when using a performance-based design. However, it is crucial that the assumptions be clearly stated and documented.

As discussed in Chapter 9, assumptions are not varied from one scenario to the next. If they are varied, then they become part of the scenario definitions. One example of an assumption taken from the performance option of NFPA 101, *Life Safety Code*, is the implied assumption that there is a single fire source or point of ignition.²² This is an assumption that applies to all scenarios, for all candidate designs.

10-6.5* Key Characteristics in Design Fire Scenarios. Scenarios should address the situations listed in Table 10-6.5 below, plus other situations of specific concern to the Technical Committee or the AHJ, to form a group of scenarios that are a mix of high and low challenge fire scenarios. The appendix material offers examples of two Technical Committees' scenario provisions. Although they use different approaches, both encompass the characteristics in Table 10-6.5.

10-7 Scenario Construction

10-7.1 General. Typically, the Technical Committee's will require the use of certain scenarios but will not fully specify those scenarios, leaving the site-specific details to be supplied by the designer with approval by the AHJ.

Table 10-6.5. Key Characteristics in Design Fire Scenarios

Illustrative Characteristics of High Challenge Scenarios
Fires in critical areas, i.e., areas where slight damage will have disproportionate impact on direct or indirect damage. Examples includes clean rooms, computer rooms, telephone switching stations, AC/DC converters and other rooms with expensive equipment highly vulnerable to even light smoke damage or with very high costs of business interruptions.
Initiating fire close to high occupancy, high fuel load, or critical areas. Examples include storage rooms near large, fully occupied assembly rooms; offices or closets near very large product storage rooms or showrooms; and plenum space fires near computer rooms.
Fire in a critical egress path, such as a front entrance way or lobby.
Fire shielded from active systems or other fire fighting activities, e.g., concealed spaces, origin outside building.
Fire involving materials producing unusually toxic, corrosive, explosive or otherwise harmful combustion products. Examples include fires exposing pool chemicals, disposal containers, or fireworks or other pyrotechnics.
Large, high intensity or fast growing fires, e.g., high initial heat release rate, flash fires, accelerant-fed arson fires, large flammable or combustible liquid spill fires.
Impairment of various fire protection systems with typical fire scenarios. For example; sprinklers with closed valves, barrier that fail to contain the fire, or detectors that fail to operate.

For example, although the example scenarios provided in Section A-10-6.5 can be applied to many buildings, they are generic and so lack needed detail for use on any particular building. For codes and standards dealing with a specific type of facility (e.g., nuclear power generating plants or furniture manufacturers using wood dust collection equipment), and even more for designs proposed for specific buildings, more detailed and site specific scenarios will be needed.

10-7.2 Considerations. When developing scenarios there are many things to consider and factor into the decision. Scenarios must be compatible with the criteria, the verification methods, the assumptions, and the proposed design, so Technical Committee's and designers should review this entire document before beginning scenario construction. There may also be other references and sources of information not listed in this document that pertain to the specific interests of individual Technical Committees.

10-7.2.1 Respecting Unique Properties of Each Design and Document. In every project a designer works on, as well as every document to which a Technical Committee might supply a performance option, there will be similar considerations, but there will also be unique ones. Despite certain similarities or "core scenarios", it is important that scenarios previously used by other projects or Technical Committees are not simply adopted without careful study of whether or not they fit the special needs of the project or document going through the performance-based process.

10-7.2.2 Occupant Characteristics. The state of the building occupants at the time of the fire scenarios needs to be considered. Any special characteristics that might be affected by specific scenarios should be noted. Section 8-2 reviews the occupant characteristics that need to be specified and developed for a performance-based design.

10-7.2.3 Environment. The environment in which the fire grows is also important to include in the scenario. Those aspects of the building environment not included in the design specifications, should be listed with the building characteristics. Detailed descriptions of the development and specification of these two facets of the design input are provided in Chapter 7 and Section 8-3 respectively.

10-7.2.4 Design Fire Details. Although the core scenarios in a code or standard will generally outline the design fire for a scenario, there will be many missing details for the designer to incorporate in order to tailor the scenario to the building being considered. Some of this information will be design specifications such as room geometry. Others will have to be assumptions based on engineering judgment, such as the heat of combustion. It is important to describe the design fire as accurately as possible.

10-7.3 Design Characteristics. This refers to the project team's proposed solution/design, expressed as quantitative parameters, variables, and other values suitable for use in an engineering calculation or test specification. The design team needs to consider all the characteristics of the fire safety system in order to evaluate the design as a whole for each scenario developed.

10-7.4* Data Use. When developing scenarios it may be useful to review statistical data. Fire experience data that matches the detailed structure of the scenarios can be useful in defining high-challenge scenarios. High-challenge scenarios can be defined as those with historically high severity, such as high rates of death per fire.

10-8 Performance-Based Provision Development.

10-8.1 General. The previous sections of this chapter have briefly introduced scenarios as part of the performance-based design process. The Technical Committees have the task of incorporating scenarios into the performance-based option of their documents. To do so, a process that will guide the Technical Committee through the necessary choices that must be made while allowing the proper amount of detail to be incorporated into each scenario is required.

10-8.2 Consider Detailed Examples. As a sample reference, Section A-10-6.5 briefly describes how scenarios are addressed in two NFPA standards already including a performance option.

10-8.3 Assistance from Support Team. Core scenarios are not intended to be in conflict with the design freedom associated with performance-based design, but, there need to be some parameters for the AHJ to evaluate the design. Overly severe scenarios mean a design meeting the prescriptive code might not pass, while insufficiently severe scenarios could

allow unsafe buildings to be built. The same situation might also result if scenario selection is excessively delegated to the design professional. While performance-based codes and standards aim to give the design professional flexibility in the design process, they are not written to allow these professionals to interpret societal values and ideas regarding what level of protection they expect from a building. In addition, not incorporating sufficient guidance regarding fire scenarios in the document could lead to conflicts between the design team and the AHJ regarding what how many and what types of scenarios should be investigated. The Performance-Based Support Team can offer more guidance to the Technical Committee on this issue.

10-8.4 Brainstorming. After reviewing this primer, it may be useful for the Technical Committee to engage in a brainstorming session to identify as many different fire scenarios associated with the scope of their document. The diverse representation of the Technical Committees is typically a good environment for thorough brainstorming.

10-8.5 Identifying Common Fires. To ensure that all of the fires which commonly occur in the type of facility covered in the code or standard in question, the Technical Committee may want to consult a fire incident data base to see if they have considered fires that statistically occur most frequently. This topic is covered in greater detail in Sections 10-7.4 and A-10-7.4. The databases presented in these sections are also useful to review how low the probabilities of high-challenge scenarios have been historically.

10-8.6 Exploratory Analysis. It may be useful to conduct exploratory modeling evaluations using a range of candidate scenario specifications, in order to examine sensitivity to parameter specification, quantitatively and realistically. This brainstorming activity can be done by the Technical Committee, or on its behalf.

10-9 Conclusion

10-9.1 General. This chapter discusses the issue of developing fire scenarios for inclusion in NFPA documents by Technical Committees wishing to incorporate performance-based provisions.

10-9.2 Development Process. Developing performance-based provisions is a dynamic process and not easily delineated. This is especially true in defining appropriate design fire scenarios. This

chapter is intended to give the Technical Committee background information and guidance in developing fire scenarios. Although reference is made to NFPA codes and standards that already include a performance-based option, the Technical Committee is not limited to those approaches. Each NFPA document is unique, which is why one Technical Committee cannot borrow another's approach without an understanding of its development and the concepts involved. Additionally, this document is not intended to replace the NFPA Performance-Based Support Team, and their assistance is available to any Technical Committee considering the development of a performance-based option within their code or standard.

Chapter 11 Design Verification

11-1 Design Verification.

11-1.1 General. Since a performance-based design will frequently involve features that do not comply with prescriptive requirements, it is necessary to verify that the design will produce a building that meets the fire safety goals and objectives. Any procedure to do this is labeled a "verification method," and Technical Committees need to provide guidelines on the selection and use of such methods.

11-1.2 Definitions. When referring to verification throughout this document the following definitions will be used:

11-1.2.1 Dictionary Definition. *The American Heritage College Dictionary* defines verification as a confirmation of truth or authority.²³

11-1.2.2 NFPA Context. In this context "verification" is to establish the accuracy of the designer's claim that a proposed solution meets the established fire safety goals, objectives and criteria. Verification involves several parts. Verification confirms that the building's ability to achieve the level of safety set in the criteria has been demonstrated by qualified people, appropriately using sound methods applied to appropriate and accurate data.

11-1.3* Verification Methods. Figure 3-2.2 depicts the role of verification methods in performance-based design and in developing performance-based provisions. The verification method is the point where one demonstrates whether a building built to the design specifications and assumptions, and confronted with the challenges of the fire scenarios, will perform in accordance with the goals and objectives, as measured by the performance criteria. As shown in Figure 3-2.2, the design specifications, characteristics, assumptions, and scenario data discussed in the previous section are required input to verification methods. The outputs of verification methods are compared to the performance criteria in order to determine the acceptability of proposed, alternate solutions.

Note: The process of evaluating, proving or validating a verification method may itself be called verification. To avoid confusion, this primer will use terms other than "verification" to

describe the process of demonstrating the appropriateness and accuracy of a verification method.

11-1.4* Selection. There are various types of tools available to use in the verification process, ranging from hand calculations to computer models (Refer to 11-2 for a more detailed description of the various types of design tools.) Each of the many types has been created to provide results for various, necessary pieces of information (e.g., system reliability or time to safe evacuation) that are required to verify a design's performance. It is important to be thorough when selecting a verification method. One must carefully consider what information the verification method needs in order to show that the criteria are satisfied, and ensure that this information is included amongst the available input.

11-1.4.1 Input. When using a tool to analyze the design, the results it predicts are dependent on the input. The input to a model or other tool is based on what is specified in the scenario, design specifications, characteristics, and assumptions as discussed in the previous chapters of this primer.

11-1.4.1.1 Characteristics, Design Specifications & Assumptions. All components of the design that are not variable need to be identified, documented and converted to input for the design tools. Those components of the design or building features that cannot be converted to output should still be identified and documented so that the AHJ is aware of this in his/her evaluation. This is crucial to the verification process because if input is omitted or misrepresented it will alter the results of the verification method.

11-1.4.1.2 Define Problem. A complete set of goals, objectives and criteria define the problem to be solved by the proposed solution and thus dictate the output to be predicted. These are essential factors to aid the designer in choosing a verification method. The design team must ensure that the verification method chosen to analyze the design produced output, which can be directly compared to the performance criteria.

11-1.4.1.3 Define Scenarios. The design fire scenarios specified or developed as described in Chapter 10, must be defined in terms compatible with the input data requirements of the verification methods. Using the detailed description of the fire scenario in question, the design team needs to define

a design fire as part of the scenario data. The design fire is the physical description of the fire including crucial information such as the fire's size, growth rate, heat release rate and other related fire properties that will be used as input in the verification method.

11-1.4.2 *Verify. After defining the problem, selecting appropriate scenarios, documenting assumptions, specifying occupant and building characteristics, and selecting a verification method, it is necessary to verify the proposed design. The method's range of output must be carefully analyzed and compared to the criteria. In doing this, the designer is verifying that the method can reasonably predict or produce the appropriate results. Results are considered reasonable if they satisfy the criteria by the pre-determined factor of safety.

11-2 Verification Methods

11-2.1 Verification Methods Available. This section is intended to introduce several types of tools that can be used to evaluate proposed solutions. Verification methods incorporate the scenario data, design specifications, assumptions, and characteristics to demonstrate that a design meets the goals and objectives of a code or standard, as specified by the criteria. Acceptable verification methods are not limited to those mentioned in this section, however, these are most commonly used.

11-2.2* Limitations. Verification methods have limitations that designers must be aware of before analyzing a design.

11-2.2.1 Background. In addition to the assumptions the designer makes in the design process, the methods that he/she uses have been developed based on certain assumptions or a complex mathematical theory that has been simplified into a usable design tool. It is important that the designer be aware of the tool's background and development, so as not to apply the verification method incorrectly.

11-2.2.2 Input Parameters. It is easy for a person doing an evaluation to overlook important parameters. A computer model will only consider that information which is input by the user.. There are many assumptions that are required in setting up a computer model and getting it to run. Therefore, in using verification methods, if assumptions are not chosen carefully and important parameters are not included, the results may not be accurate.

11-2.2.3 User. It is easy to misinterpret model results. This is especially true of computer models which are capable of predicting many different parameters. Proficiency in using models comes with experience. Computer model (as with all verification methods) results should always be checked by using at least one other verification method.

11-2.3 Deterministic Tools. Deterministic tools are based on mathematical equations which describe physical phenomena. These tools can be either dependent or independent of time, meaning they can produce results over the duration of the fire or at one, finite point in time during that duration. Deterministic tools are more commonly used than probabilistic tools. It can be speculated that this can be attributed to the fact that these tools are most often used by people with engineering backgrounds, and that these users have a better understanding of physics based models than those based on behavioral or management science. However, it is also easier to verify the results of a deterministic tool.

11-2.3.1 Hand Calculations. The simplest of deterministic tools are hand calculations. Hand calculations are mathematical equations or equation sets that can be solved using equipment no more sophisticated than a hand calculator. These equations are typically arithmetic, algebraic or differential in form, and solve for only a small number of unknowns such as physical characteristics of fire or components of egress. Various hand calculations and methods can be found in both the *SFPE Handbook* and the *Fire Protection Handbook*, as well as other professional guides and handbooks for both fire dynamics and egress calculations.^{24,25}

11-2.3.2* Physics Models. Physics models or fire models (as they are frequently referred to) do not model fires; they model the effects or physical response of a specified fire. These specified fires generally consist of a heat release rate curve input by the model user. They may be used as indicated in Sections 11-2.3.6 and 11-2.3.6.2 or by themselves to predict the performance of the design for a given scenario. For this reason they are expected to be used in most, if not all, performance-based fire protection system designs in order to predict the performance of the design. Several types of fire models are available. In order of decreasing sophistication, they are classified as: field, zone, and purpose built.

11-2.3.2.1* Field Models. Field models can provide the most detailed predictions of all the deterministic models because they divide a given space into thousands of smaller volumes. However, for other than “high end” projects, they are not practical because they are computationally intensive. These models have become more commonly known as “computational fluid dynamics (CFD) models”.

11-2.3.2.2 Zone Models. Zone models are more widely used than field models in the United States because they can provide reasonably accurate predictions in much less time. Zone models typically use less than ten volumes to depict a given enclosure. Because zone models sacrifice a certain degree of accuracy for ease of use, their predictions require a greater amount of scrutiny than do those of field models.

11-2.3.2.3* Purpose Built Models. Purpose built models are similar to zone models in their ease of use. However, purpose built models do not provide a comprehensive model; instead, they predict the value of one variable of interest. For example, a purpose built model can predict the conditions of a ceiling jet at a specified location under a ceiling, but a zone model would “transport” those conditions throughout the enclosure.

11-2.3.3 Evacuation Models. Evacuation models are used to model the behavior and movement of people during a fire situation. Evacuation model results can be incorporated into more complicated models, which couple their results with those of fire models, in order to predict the building conditions at the various occupant locations throughout the course of the fire. The design team can then determine when or if exposure will occur, and what its effect will be, and thereby demonstrate that the design does or does not meet the performance criteria. There are three categories of evacuation models that can be utilized in a performance-based design: single-parameter estimation methods, movement models, and behavioral simulation models.

11-2.3.3.1 Single-Parameter Estimations. Single-parameter estimation models are generally used for simple estimates of movement time. They are typically based on equations derived from observations of movement in non-emergency situations. They may be hand calculations or simple computer models. Examples include calculation methods for flow times based on widths of exit paths and travel times based on travel distances. Sources

for these methods include the *SFPE Handbook* and *Fire Protection Handbook*.

11-2.3.3.2 Movement Models. Movement models do not model the movement of individuals, but rather generally handle large numbers of people moving in a flow network similar to water in pipes or ball bearings in chutes. They tend to optimize occupant behavior, resulting in predicted evacuation times that can be unrealistic and far from conservative. However, they can be useful in an overall assessment of a design, especially in early evaluation stages where an unacceptable result with this sort of model will indicate that the design has failed to achieve the life safety objectives.

11-2.3.3.3 Behavioral Simulation Models. Behavior simulation models take into consideration more of the variables related to occupant movement and behavior. Occupants are treated as individuals and can have characteristics assigned to them uniquely, allowing a more realistic simulation of the design under consideration.

11-2.3.4 Sources of Computer Fire and Evacuation Models. Compendia of computer fire models are found in surveys and directories developed by Factory Mutual and SFPE, as well as the Forum for International Cooperation in Fire Research - International Survey of Fire Models web site.^{26,27,28} Additionally, the models described in these sources and developed by the Building Fire Research Laboratory of National Institute of Standards and Technology, may be downloaded from the Internet at <http://www.bfrl.nist.gov/864/fmabs.html>. Further discussion of various evacuation models can be found in the proceedings of conferences such as *Interflam 96 - Seventh International Fire science and Engineering Conference* and the proceedings of the *First International Symposium on Human Behavior in Fire*.^{29,30} Peer reviewed papers on evacuation models can be found in documents such as the proceedings of *IAFSS Fifth International Symposium - Fire Safety Science*.³¹ Other calculation methods can be found in both the *SFPE Handbook* and the *Fire Protection Handbook*.

11-2.3.5 Validation of Computer Fire Models. Computer fire models undergo limited validation; i.e., they are applicable to either the experimental results upon which they are based, and/or the limited set of scenarios to which the model developers compared the initial set of model output. The Society

of Fire Protection Engineers has formed a task group to independently evaluate computer fire models. The task group should complete their first evaluation (DETECT) early in the year 2000, and have chosen a second model (ASET) to evaluate. Until more models can be evaluated independently (i.e., not by the developer), the model user must rely on available documentation and previous experience for guidance regarding the appropriate use of a given model. By choosing a specific model, the user is tacitly assuming that the model is valid for the scenario under consideration.

11-2.3.6* Non-Fire Models. In addition to the fire and evacuation models described in this section, the Technical Committee may have to specify special model types depending on the scope of the code or standard in question. The Technical Committee should provide a description of the model types, along with any requirements that might be necessary. Additionally, the Technical Committee should provide a list of sources for these model types if they are specialized in nature, and difficult to obtain.

11-2.4 Test Results. Test results may be used to provide special data required by a model, or to directly verify a proposed solution if the test conditions adequately and accurately represent the scenarios. The Technical Committee should stress that one must be careful not to misinterpret the scenario in order to make it conform to the test.

11-2.4.1 Data Uses. The data obtained from standardized tests has three uses for verification purposes. The test results can be used instead of a model (This will typically be the role of full scale test results). The test results can be used as a basis for validating the model (If the model predictions match well with the test results, the model can be used in situations similar to the test scenario). Finally, the test results can be used as input to models (This is typically the use of small scale data tests).

11-2.4.2* Experimental Data. Experimental data may be used as a verification technique when the specified scenario and the experimental setup are similar. Typically, experimental data are applicable to a greater variety of scenarios than are standardized test results. Experimental results can also be used as input for modeling or compared to the output of a predictive model as part of a validation exercise.

11-2.4.3 Standardized Tests. Standardized tests are conducted on various systems and components to

determine whether or not they meet some predetermined criteria. These tests are by their nature prescriptive, as the results are given on a pass/fail basis: the test specimen either does or does not meet the pre-established criteria. The specific time history performance of the test specimen is not usually recorded.

11-2.4.4 Scale. Tests can be either small, intermediate, or full scale. Small scale tests are used to test activation of detection and suppression devices, and the flammability and toxicity of materials. Usually, the item to be tested may be placed within the testing device or apparatus. Intermediate scale tests may be used to determine the adequacy of system components, e.g., doors and windows, as opposed to entire systems. The difference between small and intermediate scale is usually one of definition provided by those conducting the test. Full scale tests are typically used to test building and structural components or entire systems. The difference between intermediate and large scale is also subject to the definition of those performing the test. Full scale tests are intended to most closely depict performance of the test subject as installed in the field; i.e., most closely represent real world performance.

11-2.4.5* Start-up Tests. Start-up test results can be used to demonstrate that the fire protection system performs as designed. The system design may be based upon modeling. The start-up test essentially verifies the system design modeling and confirms that the system performs as designed and intended. Start-up tests and system design modeling are not the same as verification methods for an entire building design of which the system is a part. If the start-up test indicates a deficiency, then the system must be adjusted and re-tested until it can be demonstrated the system performs as designed and intended. Only then can one ask whether system performance and the rest of the building design meet the criteria for the building. Typically, start-up tests apply only to the installation of the system component for which they are designed.

11-2.5* Probabilistic Tools. A probabilistic tool is one based upon the probability of occurrence of various events. These tools often use statistics to estimate probabilities.

11-2.5.1 Expected-Value Risk Model. It is possible to use probabilities in a very restricted fashion as part of a model of risk based on expected value. Such a

model can use the probabilities of occurrence of scenarios to weight estimates of scenario consequences, where the consequences are estimated using deterministic tools. The weighted consequences are then summed to produce the risk estimate.

11-2.5.2* Probabilistic Tree Model. A tree model is an example of a fully probabilistic model. A tree model can be either logic or time dependent. In a logically dependent tree model the flow can trace an event through success or failure (e.g., success or failure tree). In an event tree (time dependent), probabilities are used to indicate whether a particular event will occur, given occurrence of a prior event (e.g., people will reach the front door, given that they have moved half-way through the lobby vs. being still asleep in bed).

11-2.5.3 Special Sub-Model. A partially or fully probabilistic tool can be used to provide input for a more complex deterministic model. This reflects the fact that any phenomenon can be modeled probabilistically, and some aspects of a fire safety analysis such as ignition or reliability cannot be reliably and appropriately modeled deterministically.

11-2.6* Heuristic Tools. A heuristic tool is one that is based on investigation, problem solving techniques, experience, and especially engineering judgment. It is a successive process in which the decisions made at one step bear a direct effect on the outcome and direction of the ensuing step.

11-3 Verification Method Selection. The design team will have to select a verification method that generates output data which can be directly compared to the performance criteria. While a Technical Committee generally will not specify that an exact type of verification method be used, they may place restrictions on certain model or calculation types.

PART V – DESIGN ACCEPTANCE AND APPROVAL

Chapter 12 Design Acceptance

12-1 General. The basic intention of a performance-based design is to ensure that the specific, proposed building satisfies the goals and objectives specified in the code or standard. The determination of whether a building satisfies these goals and objectives is made by comparing the design output, determined by the verification methods using the input developed from the specific code requirements and the proposed building design, against the performance criteria developed by further quantifying the goals and objectives.

The many sources of uncertainty inherent in the design process need to be analyzed and addressed, e.g., by applying a safety factor to the design output before the comparison with performance criteria is made. The Technical Committee may provide requirements or guidance on the analysis and interpretation of uncertainty, including the specification of safety factors. The comparison of the output to the criteria will determine whether the design meets the fire safety goals and objectives of the code or standard, and is acceptable to the engineer, or does not meet the goals and objectives and must be modified and re-evaluated. This process continues until a design satisfies the performance criteria. If multiple designs are found to satisfy the criteria, then the stakeholders can decide which option is most appealing based upon a variety of options including, but not limited to, cost, functionality, ease of construction, actual level of safety, and aesthetic quality.

12-2 Design Output. The design output consists of all of the conclusions and data obtained from the verification method or design tool used to evaluate the proposed design. The design team must ensure that they select a design tool or verification method that will produce output in engineering terms that can be directly compared against the performance criteria. If the verification method selected produces additional output results that cannot be compared to the performance criteria, yet are still relevant to the building's performance, these shall be included in the submittal to the AHJ.

12-3 Uncertainty in Performance-Based Fire Safety. While performance-based design allows engineers to design a building and calculate the level

of performance or safety, the process involves a level of uncertainty not considered under prescriptive codes and standards. Custer and Meacham define four sources of uncertainty in acceptable-risk solutions and performance-based design: uncertainties about terminology; uncertainty relating to the science and engineering involved; uncertainty regarding risk perception; and uncertainty about the usefulness or importance of individual and societal values (e.g. "how safe is safe enough").³² The Technical Committee should meticulously define each facet of the performance-based terminology in the code or standard, eliminating much of the uncertainty regarding terminology. Additionally, the Technical Committee will specify the goals and objectives of the code or standard under consideration, limiting, but not eliminating, the uncertainty regarding risk perceptions and values. Note that scenario choices and assumptions will also quantify and specify societal values, and the process for defining them will have some uncertainty associated with it.

The Technical Committee is least able to affect the uncertainty relating to the science and engineering involved in the performance-based process. Included in the uncertainty of the science and engineering are uncertainties relating to some of the assumptions made by the design team, including values for the building and occupant characteristics, and uncertainty relating to the applicability and level of accuracy of the verification methods. Each of these uncertainty values will have to be addressed in the design, limiting the potential impact final design outcome and ensuring a safe design.

12-3.1* Conservative Values. In order to limit the uncertainty associated with the input variables, the design team should select appropriate, conservative values for assumptions, and building and occupant characteristics. Included in the submittal to the AHJ should be specific references for each of the input variables whenever possible, allowing the authority having jurisdiction to determine the level of conservatism used in the selection of input values. The design team must be sure that the use of overly conservative values in one aspect of the design does not produce the opposite effect in another aspect of the design.

12-3.2* Sensitivity Analysis. Part of an uncertainty analysis typically consists of a sensitivity analysis on the input parameters. A sensitivity analysis entails the changing of one or more variables in the input to

determine how these changes affect the results of a method or model. If small uncertainties in input translate into large variations in predicted hazard or risk, conventional safety factors (e.g., a factor of two) may be insufficient. If large uncertainties in input translate into small variations in predicted hazard or risk, conventional safety factors may be more conservative than necessary.

The initial evaluation run of the verification method should be labeled the base case, and each subsequent run labeled as to which variables have been modified. The overall intent of a 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; inform and caution potential users about the degree and level of care to be taken in selecting and using the method or model;³³ and guide the setting of safety factors and the evaluation of candidate designs as safe or unsafe.

12-3.3* Safety Factors for Design Variables.

Performing a sensitivity analysis on the input parameters of the verification method or model will not account for all of the uncertainty relating to the science and engineering involved in the performance-based design process. In order to account for any remaining uncertainty involved in the entire design process, safety factors should be applied to the design variables. The Technical Committee should require the use of an approved safety factor, whose numerical level may be specified by the code or standard or left to the local jurisdiction.

Figure 3-2.2 depicts the safety factor being applied directly to the design output; however, the Technical Committee can specify that these factors be applied at other stages of the design. Perhaps the simplest manner in which a safety factor can be applied is at the design output. An example would be simply using a safety factor of 2 to double the time for occupant evacuation before comparing this time to that of the spread of fire products of combustion.

This example also illustrates the limitations of safety factors, which are intended to compensate for uncertainty, not gaps in the analysis. An evacuation time that omitted a key component (e.g., pre-movement time) would not become valid, let alone conservative, if multiplied by a safety factor designed to compensate for the uncertainty in the calculation of time components that were included.

Application of a factor of safety during the design input stage is also possible, but one must ensure that this application does not produce undesired, non-conservative results. If the safety factor is to be implemented at this stage in the analysis, the Technical Committee should include requirements for analyses demonstrating that this application does not lead to non-conservative results in any phase of the design.

Chapter 13 Reliability in Performance Based Design

13-1 General. No design feature is totally reliable. Traditionally, acceptable design reliability has been achieved through a combination of standards and procedures to achieve acceptable reliability for each design system or feature and through redundancy requirements, that is, prescriptive requirements for the inclusion of multiple systems and features that might not all be necessary for safety if one could be sure that all would perform as designed in any fire. The challenge is to address legitimate reliability concerns in a performance-based environment without mandating needlessly expensive inspection, maintenance, or redundancy requirements.

13-2 Definition. Given the nature of a performance-based approach (i.e., flexible), the definition of terms becomes an important issue. Therefore, an authoritative definition of “reliability” is presented, followed by the term’s envisioned use in NFPA documents.

13-2.1 Basic Engineering Definition. Statistical and engineering references all define “reliability” for engineering purposes as some variation of the following: “the ability of an entity to perform a required function under given conditions for a given time interval.”³⁴

13-2.2* NFPA Context. In this context “reliability” is used to establish the accuracy of the designer’s claim that a proposed solution not only will meet the established fire safety goals, objectives and criteria if the design performs as intended, but that the design will perform as intended -- or close enough -- with sufficiently high probability. It may be useful, in making distinctions, to use the term “operational reliability” to refer to the likelihood that a system or feature will perform at all in response to a need, and the term “performance reliability” to refer to the likelihood that the system or feature will respond effectively and appropriately in response to a need, given that it has performed at all.

13-2.3 Definition Scope. Reliability is not limited to all-or-nothing failures. Any deviation from designed or intended performance constitutes less than perfect reliability, but it may be overly conservative to evaluate partial failures as if they were complete failures.

13-3 Role of Reliability in Performance-Based Design.

13-3.1* Equipment vs. Human Reliability. Reliability is not entirely, or even primarily, about mechanical or electrical reliability. For most design features and systems, the leading cause for failure to perform as designed during a fire is some human error or oversight that partially or totally defeats the feature or system.

13-3.2 Active System vs. Other Reliability. Reliability concerns are not limited to active fire protection systems or even to built-in or physical features and systems. Any specification in a design and any assumption regarding manufacturing, construction, installation, maintenance, operation, supporting behavior, or any other aspect or phenomenon whose success is expected to contribute to the achievement of fire safety objectives will have an associated reliability, consisting of the probability that that aspect will perform as designed, intended, or expected in fire.

13-3.3 Liability Concerns. There will be concerns that explicit acknowledgement of less than perfect reliability is an invitation to liability. It is more likely that failure to acknowledge – and address – less than perfect reliability is an even more sure invitation to liability. The reliability issue will not go away just because it has not been explicitly acknowledged. The Technical Committee’s intentions with regard to safety in their area of responsibility will be far clearer and more likely to be accurately and fully implemented if the committee has made its views known on reliability.

13-3.4 Incorporating Reliability Into a Performance-Based Assessment. Figure 3-2.2 depicts the elements of a performance-based design. Reliability is not explicitly shown, but it may be addressed at any or all of the calculation points in the flowchart, including, but not limited to the proposed building design, the specification of appropriate assumptions, or the development of adequate fire scenarios and specification of appropriate scenario data. No matter where it is addressed, reliability can be the basis for deeming a proposed design unacceptable, which will require a modification to the design before it is submitted again.

13-3.4.1 Addressing Reliability Through Scenarios. Reliability can be addressed in the development and specification of scenarios if

specification of the status of design systems, features, and aspects is part of the scenario development exercise, by having some of the selected scenarios specify impaired, or less than perfect, status. Scenarios can be defined to “fail” different systems or features individually, and a series of scenarios can be used to work through all the main systems or features and assess the impact of unreliability for each one. Or, scenarios can be designed to “fail” more than one system or feature at a time, which is a more severe test of overall redundancy. This may be justified if, for example, the failure of one system poses a significant threat of failure to another system or feature, or if external common causes (e.g., earthquake) can cause simultaneous failure of more than one system or feature. This method of addressing reliability in the development of fire scenarios is also presented and discussed in Section 10-6.5 and A-10-6.5.

13-3.4.2 Addressing Reliability Through Objectives. Reliability can be addressed in the objectives by requiring an acceptably high level of reliability as one or more of the objectives. This may require specification of a practical means for measuring or estimating design reliability.

13-3.4.3 Addressing Reliability Through Assumptions. Reliability can be addressed in the assumptions by assuming a level of reliability, but such assumptions ought to be substantiated by some form of direct evidence. By contrast, a blanket assumption that all design elements are reliable, without any direct evidence, is tantamount to ignoring the reliability issue entirely. Since reliability is a real issue with any design and associated analysis, the reliability issue must be addressed somewhere. If it is not addressed within the code or standard, there should be some formal acknowledgement of where and how it is expected that the issue will be addressed (e.g., in referenced standards for installation and maintenance, or possibly in product standardization requirements falling outside the NFPA system).

13-3.4.4 Addressing Reliability Through Verification Methods. Some verification methods, notably full fire risk assessments, permit the designer, with approval from the AHJ, to calculate the impact of reliability on the estimated fire safety performance of a design. This is usually a variation of addressing reliability through scenarios, but it includes the use of measured or estimated reliability probabilities to combine design performance in

perform-as-designed scenarios with performance in not-perform-as-designed scenarios into an overall measure of design merit. That is, use the verification methods to calculate fire safety performance when the system or feature is reliable (works as designed) and fire safety performance when it is not reliable (does not work at all or does not work as designed), then combine the two using an externally calculated probability of reliability.

13-3.4.5* Addressing Reliability Through Factors of Safety. Safety factors can sometimes be used mathematically to address reliability, but it is important to understand that that is not the purpose behind safety factors. Using safety factors to address reliability implicitly assumes that the effect of the feature or system unavailability or unreliability takes the same form as a quantitative change in the performance of the feature or system when operational. This is dubious at best. It is not clear that the effect of disabling the detection/alarm or sprinkler system will be the same as the effect of a delay in the time of activation of those systems or a reduction in the speed with which operating sprinklers control fire. It is more reasonable to assume that the effect of blocking open the lobby doors can be reflected in a safety factor on the speed of spread of fire effects.

Generally speaking, though, treating reliability through safety factors is mixing apples and oranges, and should be discouraged, or if not discouraged, carefully scrutinized to see whether the real issues of reliability are captured and addressed. Do not assume that a sufficiently large safety factor will render moot the reliability concerns of all the individual systems and features. If a large safety factor accomplishes that goal, it will be a lucky side effect and not the purpose or intended effect of the safety factor.

13-4 Methods of Addressing Reliability

13-4.1 Reliability in a Risk Analysis versus Hazard Analysis Framework. A performance-based assessment of a building may be done in either a risk analysis or a hazard analysis framework. In a risk analysis framework, all possible scenarios are considered through analysis of the probability and severity of a representative group of scenarios. In such a framework, reliability concerns become simply one more set of characteristics to consider in defining scenarios, and the impact of reliability on the design’s performance is picked up naturally in the

analysis. More commonly, however, engineers will use, and performance-based codes and standards will employ, a hazard analysis framework.

13-4.1.1 Probability Thresholds in a Hazard Analysis Framework. In a hazard analysis framework, probabilities are not considered directly. Safety is assured when it is possible to give a satisfactory answer about the design for any scenario. The answer for most scenarios is: The design achieves the specified fire safety goals, objectives, and criteria for the scenario as demonstrated by application of an appropriate verification method, using appropriate assumptions, to either that scenario or to a similar scenario that is more challenging. The answer for some scenarios is: The design cannot assure achievement of the fire safety goals, objectives and criteria for this scenario but should not be required to because the scenario is so unlikely or has been explicitly declared outside the scope of the requirements, usually because Technical Committee or AHJ deemed it to be technically infeasible or unacceptably costly to meet the goals, objectives and criteria for that scenario. If low probability is the reason for not incorporating a scenario into the evaluation, then there is an implied minimum threshold of probability that is part of the code's definition of acceptable risk and acceptable safety.

Thresholds also may be embodied in the objectives (e.g., NFPA 101, *Life Safety Code* does not require protection of people intimate with ignition because the reasonable choices available to designers cannot assure such protection). Thresholds also may be embodied in the assumptions (e.g., in the *Life Safety Code* provisions for residences, occupants are assumed to be capable of acting effectively to respond to a fire by evacuating, even though it is known that a fraction of the population living at home lack such capability). Each threshold corresponds to a minimum or maximum condition with an associated implied probability.

13-4.1.2 Reliability as a Probability Threshold in a Hazard Analysis Framework. If it is reasonable to regard acceptable safety as the assurance that fire safety goals, objectives, and criteria will be met for all fire scenarios likely enough to justify attention, then a system or feature failure, partial or complete, is a rare event that makes an already unlikely fire scenario even more unlikely. To bring the scenario back to the implied minimum probability threshold, some other aspect of the calculation must be made more likely. This is a mathematical argument (based

on equivalent risk) for relaxing the scenario, the assumptions, or the goals, objectives, and criteria when evaluating a design's performance under partial or complete failure of a system or feature.

A less severe initiating fire would qualify as such a relaxation. So would less conservative assumptions about occupants or other relevant conditions not part of the design. And a less ambitious goal, achieved by reducing the scope of potentially affected people or property who must be saved for the design to be successful, could also be handled in this way, even if such a modification does not involve probabilities in as obvious a fashion.

It is also possible to assume that a certain level of reliability, high but less than perfect, is implicit for each system, feature, and aspect in the current prescriptive codes and standards. A performance-based assessment of an alternative design should be evaluated against that baseline, not a baseline of prescriptively required systems, features, and aspects, all with perfect reliability. Each of the elements of performance-based assessment where reliability can be addressed corresponds to a particular practical method of addressing reliability.

13-4.2 Addressing Reliability Through Scenario Design. A common engineering practice is to test a design, first with all systems and features operating as designed against a specified fire scenario, then successively with each system or feature individually removed from the design, or at least reduced in effectiveness. For a performance-based code or standard, this common engineering practice can be made mandatory by specifying one or more scenarios in which each major fire protection system or feature, in turn, is removed from the design or reduced in effectiveness, as discussed in Sections 10-6.5 and A-10-6.5. In this approach, the initiating fire or other assumptions are made less severe to keep the overall scenario probability comparable to that for other scenarios.

The advantages of this approach are that it seriously treats reliability concerns, that it uses the already established performance-based analysis framework and so does not require any new methods or data sources, and that it provides strong incentives for redundancy.

The disadvantages of this approach include the following: It gives no credit for reliability that is very high but still less than perfect, and so this

approach provides no incentive to achieve higher reliability. It tends to encourage consideration of total failure events over partial failure events, no matter how great the difference in probability is between total and partial failure. Some systems or features may be so essential to designs for some facilities that their removal will leave no reasonable way to achieve the goals, objectives, and criteria, if those remain unmodified. Finally, if you follow the logic of this approach to its conclusion, you would have to consider simultaneous failures of multiple systems and features; in such scenarios, even traditional redundancy might not be sufficient.

13-4.3 Addressing Reliability Through Assumptions. The simplest way to address reliability through assumptions is to assume that all systems and features are reliable. The advantages of this approach are its simplicity and the fact that this assumption is implicit, to a large degree, in many of the prescriptive codes and standards -- all those without provisions for assuring reliability or for significant redundancy. The disadvantages of this approach are that it does not really address reliability in any meaningful sense, and that it creates substantial incentives to reduce redundancy for cost reasons and to accept low reliability in individual systems or features, either inadvertently or to save money on the programs required to assure high reliability.

A more substantive way to address reliability through assumptions is to create a two-track approach. Any design providing evidence or assurances of reliability and redundancy equivalent to those in a design compliant with the prescriptive code or standard will be assumed to have acceptably high reliability and sufficient redundancy. No further analysis or proof of acceptability on reliability grounds will be required. Any design not providing such evidence or assurances is required to address reliability more directly and explicitly, for example, through analysis of designated scenarios.

The advantages of this approach are that it seriously addresses reliability concerns, and that it makes maximum use of established codes and standards and the expertise they embody on acceptable, achievable levels of reliability and the means required to achieve them. The disadvantages of this approach are that it provides no incentive for reliability higher than current implied requirements, and that it may rely on more extensive provisions than are included in the current prescriptive codes and standards. Not every

application of every system and feature required in an NFPA code or standard has a complete associated standard to assure acceptable reliability.

Another way to address reliability through assumptions is to assume a lower occupancy load or greater occupant capability when features or systems are impaired or removed. A conservative approach might assume that, with all systems and features operating, the design should be able to protect all occupants in a fully loaded -- even somewhat overloaded -- building, including the most vulnerable and least capable people (e.g., older adults, young children, disabled persons, people impaired by drugs or alcohol). For a reliability analysis with a key system or feature removed or impaired, the design might be evaluated only against a more typical, less conservative occupant set, such as a building occupied to 60% capacity with all occupants consisting of fully capable adults. The advantages and disadvantages of this approach are similar to those of addressing reliability through scenarios.

13-4.4 Addressing Reliability Through Objectives. One means to address reliability is through the specification of objectives by the Technical Committee. As an example, the NFPA 101, *Life Safety Code* seeks to protect everyone in the building except people intimate with ignition.³⁵ It may be, even with a milder, relatively slow initiating fire and more typical, less conservative assumptions as described above, that the design cannot assure protection of all those people in the absence of some key feature or system. But the alternative need not be to treat any level of performance as acceptable. The goal could be reset to protection of everyone in the room of origin or on the floor of origin or within 100' of the point of fire origin. By considering the combined effect of the systems and features regarded under the prescriptive code or standard as sufficient for redundancy, and analyzing the point in time, the speed, and the manner in which they operate, a Technical Committee can identify a less demanding goal.

13-5 Incorporation of Reliability in Codes and Standards

13-5.1 General. When addressing reliability in their documents, Technical Committees will want to indicate data, assumptions, verification methods, and documentation requirements for designers that will give AHJ's the information they need to evaluate the treatment of reliability in the design analysis.

13-5.2 Unique Data Issues for Reliability. A unique problem for reliability is that data is very scarce and, where it exists, tends to exist only for highly specialized products (e.g., products built to military specifications for highly demanding environments) or highly unusual applications (e.g., systems with unusually thorough ongoing maintenance, inspection, testing and supervision arrangements) or severely biased data collection regimens (e.g., laboratory tests on time to failure distributions without data on human error reliability).

The detailed limitations of available data bases and the appropriate steps to take in using them to address reliability for a particular design typically will not be the province of the Technical Committee. Referenced engineering guides should provide guidance on these steps and may provide references to data bases. However, it is reasonable for Technical Committees to explicitly recognize the issue, possibly in the form of a documentation requirement for special attention to the match, or mismatch, between the design elements in the designer's proposal and the design elements (and supporting ongoing safety and quality assurance programs) reflected in the design analyst's referenced data bases.

Chapter 14 Documentation

14-1 Design Documentation and Presentation. A performance-based code or standard should provide flexibility to the design team when designing and evaluating a building. Despite allowing this flexibility in the design, the Technical Committee should include requirements for proper documentation, which will ease the burden of reviewing performance-based designs on the AHJ. The code or standard should ensure that all aspects of the design are incorporated in the submittal to the AHJ for his/her review. Proper documentation is essential to the implementation of a performance-based design, and will ensure that each stakeholder understands what is necessary for design implementation, maintenance, and continuity of the fire protection design.³⁶ In order to simplify the review process, the documentation submitted to the AHJ shall be written in a clear and concise manner. The design submittal shall be separated into three parts: the Design Report, the Specifications and Drawings, and the Operations and Maintenance Manual. The specification of a thorough and complete documentation procedure is extremely important, and when properly completed and laid out, the report can be used by the authority responsible to review the structure as the performance-based fire code. Using the design documentation as a baseline, the reviewer can ensure that the design input values remain valid, and that the fire scenarios still apply to the structure.

14-2* Design Report. The design report will serve as the primary means of description for the fire protection system design, as well as a complete description of this design's evaluation and performance. Although each jurisdiction and each design firm will have different preferences for how the information should be presented and arranged, the Technical Committee should have requirements on at least the required contents, and at most the required layout. The more rigid the requirements become, the more simplified the review process will become, as the AHJ will be able to develop a standard procedure for the review of performance-based design reports. The appendix provides one example of a design report layout. This example is separated into various sections for each aspect of the design, and can be used by the Technical Committees to develop specific requirements for the design report content and layout for the code or standard in question. An alternative outline for the design report submittal is include in the SFPE design guide.³⁷

Despite differences in requirements regarding the report layout, the overall requirements for content included in the design report should be similar.

14-3 Specification and Drawings. The specifications and drawings provide the AHJ, the building and system designers, and the installation contractors, with a means to implement the performance-based design. The detailed specifications should include information such as required sprinkler densities, automatic detector or sprinkler spacing, or location and description of fire resistive walls. The specifications should serve as the implementation documents for the performance-based design.³⁸ The detailed drawings shall be included to provide a graphical representation of the design and specifications.

14-4 Operations and Maintenance Manual. The Operations and Maintenance (O+M) manual outlines the requirements of the building operator to ensure that each aspect of the design is maintained operational throughout the life of the building. This document acts essentially as the users guide to the performance-based aspects of the building. The manual should provide a description of each of the individual fire protection systems, as well as a description of how these systems interact to meet the fire safety goals. The manual should outline a maintenance and testing schedule for each system, both individual and as a complete design, necessary to maintain their performance requirements. An additional part of the O+M manual consists of restrictions placed on the building operator and tenants regarding assumptions or estimations made by the design team as to the fire load, building use, occupant characteristics, and system reliability. The O+M manual should outline procedures which can be taken by the building operator to ensure that these assumptions remain valid throughout the life of the building. The Technical Committee should include text stating that the O+M manual can also be used by the AHJ as a basis for reviewing the structure, acting as a performance-based fire code for that particular building. For example, the AHJ could develop a checklist to ensure that each of the input values remains valid, and that the fire protection systems and features have been tested as outlined in the manual.

The final sections of the O+M manual should outline procedures to be taken if components of the complete fire protection system are removed or impaired temporarily or permanently. These procedures

should be based upon the importance of the system component to the overall fire protection system design, as well as the duration of the operational impairment. These compensatory measures are critical to building performance, and the design team should attempt to consider every possible impairment or system breakdown which might occur during the intended use of the building.

Chapter 15 Approval Process

15-1 General. The approval of the AHJ is the terminal activity in the design stage, and it is his/her decision to either give approval or request further verification of the proposed solution. It is not the role of the AHJ to judge whether or not a prescriptive design could have been done in place of the performance-based design submitted; only to evaluate the design he/she receives. In some jurisdictions, there may be multiple authorities having jurisdiction over the design. One example is a jurisdiction with a building official, who oversees the structural, mechanical, and other features and systems of a building, and a fire marshal who oversees all fire protection features and systems within the building. In this case, each authority would have the opportunity to review the design.

15-2 Design Approval. After receiving a complete submittal from the design team, including the Design Report, Specifications and Drawings, and Operations and Maintenance Manual, it is the prerogative of the AHJ to give approval of the design or request further verification. In order to facilitate the design approval, the design team should involve the AHJ early in the process, seeking approval or the various components of the design before beginning the evaluation process. Different jurisdictions may have different requirements regarding values for occupant characteristics or assumptions, and the design team should meet with the AHJ to clarify the intentions of the design, as well as determine any special requirements for that particular jurisdiction. The involvement of the AHJ in the design process as early as possible will simplify the procedure and the selection of the various input variables, and allow the design team to develop a good working relationship. This relationship should allow the design team to submit a design that will meet the AHJ requirements without the need for additional verification or re-submittal.

15-2.1 Training and Re-education. Due to the engineering and calculations that serve as the foundation for performance-based designs, special training may have to be provided for AHJ's who have to review and approve these designs. This training should focus on appropriate values for the design input and safety factors, as well as necessary levels of verification used to evaluate the design. Periodic training certification sessions would also ensure that the AHJ stays current with advancing

technology and abreast of research on the input variables and performance criterion.

15-2.2 Third Party Review. The AHJ must be able to recognize the limits of his/her evaluation expertise and schedule. If these limits are exceeded, the AHJ should seek the services of a third party reviewer. The third party reviewer is a person or group of people chosen by the AHJ, with the help of the building owner, to assist the AHJ in reviewing the design submittal and determining if the fire safety objectives have been met by the design. The third party reviewer must be qualified, and must be able to demonstrate experience in either designing or reviewing performance-based documents, a good working knowledge of the jurisdictional documents, and a familiarity with the scope of the project. The cost of a third party review shall be the financial responsibility of the design team or owner. Consequently, they have the right to object to the selection of the person or group of persons who were chosen to complete the review, based purely on their opinions regarding the qualifications of the reviewer. The third party reviewer, acting as a consultant to the AHJ, is obligated to make a thorough and fair evaluation of the building design.

15-3 Building Maintenance and Risk Management. The building owner or the person responsible for maintaining the structure should take measures to ensure that the assumptions and specifications used to analyze the building remain valid throughout the life of the structure. Failure to do so may increase the level of risk posed by the building. When documenting the building design and evaluation, the design team should include information on the assumptions in the submittal to the AHJ, and document how the building is to be maintained in order for the input values used in the design to remain valid. In addition to the design team and the building operator, the authority responsible for reviewing the building design, construction, and the maintenance of the structure must understand the level of the hazard and risk explicit in the building design, and how these levels are to be maintained throughout the life of the structure.

The authority should consider the level of risk posed by the building design and the need to maintain the input values when conducting periodic reviews of the structure in order to maintain this level of risk. If the authority becomes aware of a failure to maintain the original input parameters used in the design, he/she

can require a re-evaluation of the building to ensure that there is no increase in risk.

15-4 Management of Change. A performance-based design will remain valid only as long as the actual building conditions remain consistent with the design input variables. A change in one or more of these variables can result in the building no longer satisfying the performance criteria. If the values selected for the characteristics and assumptions are no longer applicable, or a modification is made to the design specifications, the Technical Committee should require the building be re-evaluated to ensure that it satisfies the original goals and objectives to which it was designed. The overall amount of re-evaluation required shall be dependent on the magnitude of the deviation from the original design input. If a simple modification, such as a change in the interior finish materials is proposed, then the re-evaluation might consist of a review of the original design to ensure that the flammability characteristics of this new material remain within the levels covered by the sensitivity analysis on this parameter, or that this change will not dramatically alter the fire scenarios used in the original evaluation. However, if something more dramatic, such as a change from a business occupancy to a mercantile occupancy is proposed, then the design would require a complete re-evaluation, including the possible development of new assumptions, characteristics, design fires, and building specifications.

PART VI - TECHNICAL COMMITTEE USE

This section (Part VI) is included to give general Technical Committee guidance and sources of references for their documents, including a performance-based option.

Chapter 16 Technical Committee.

16-1 General. This primer has outlined the steps and components which could be used by a Technical Committee to develop a performance-based document. If a Technical Committee intends to add a performance-based option to their code or standard, this document can be used as a general guide on what type of information should be included. Many of the concepts presented in this primer will be applicable to most performance-based codes and standards. However, the Technical Committee should avoid simply copying this information into the code or standard without a thorough review of all of the material presented, as each code and standards is inherently unique.

16-2 Performance-Based Document Development.

The intention of this document is not to present a method that can replace the current prescriptive language found in most codes and standards, but instead to present an option that can be added to an existing code or standard, allowing a designer to choose between a performance or prescriptive document. Examples of NFPA documents that have been written in a performance-based language or contain a performance-based option, include NFPA 92B, *Guide for Smoke Management Systems in Malls, Atria, and Large Areas*, which is an entirely performance-based document, and the 2000 edition of NFPA 101, *Life Safety Code*, which includes a performance-based option as well as the traditional prescriptive approach.^{39,40}

16-3 Using the Performance-Based Option. If a Technical Committee includes a performance-based option in a code or standard, it is up to the designer to decide whether or not to use the performance option or the familiar prescriptive requirements. Sufficient explanation must be incorporated into the document to expedite the use of the performance-based option. Additionally, the Technical Committee must include sufficient requirements and references, even within the performance option, in order to limit potential, typically unintentional, abuses on the part of the designer.

16-4 Performance-Based Design Guide. Several times in this document, reference has been made to the SFPE performance-based design guide. This guide, to be released in early 2000, provides the designer with an outline of the performance-based design process. This process is similar to the one presented in this document, and will act as a resource for the designer to use when designing according to performance provisions.

Appendix A

This Appendix is not part of the recommendations of this NFPA document, but is included for information purposes only.

A-2.1 Bottom-Up. It is called "bottom-up" because it works "up" from the established prescriptive language to infer the goals, objectives, and other statements that justify the prescriptive language.

A-2.1 Calculation Method. More specific terms including the word "model", such as computer model, fire effects model, evacuation egress model, and computer fire model are often used as a synonym for "calculation method". The more specific term will be used in this document where applicable

A-2.1 Design Specification. The design team should include any design specifications which can be used as input for the design tools, or will impact the assumptions made by the design team. The design specifications listed by the design team should be separated into categories of those that can be readily changed by the fire protection design team, and those that cannot be easily changed by the fire protection design team and would instead require major changes to the overall structural and architectural building design. Included in the first category would be items such as, but not limited to, the ventilation flow rate, sprinkler density, interior finish material (and consequently its flammability), whereas the second category would include items such as, but not limited to, building height, building footprint, floor height, etc.

Figure A-3-2.2 Performance-Based Design Process

Title	Description
Code or Standard Fire Protection Goals	Code or standard required fire protection outcome presented in a non-specific, qualitative basis.
Project Team Fire Protection Goals	Basic fire protection desires of stakeholders not specifically stated in, or required by, the code or standard.
Fire Safety Goals	Overall outcome to be achieved with regard to fire, measured on a qualitative basis.
Fire Safety Objectives	Requirement for the fire, building, or occupants that must be satisfied in order to achieve a fire safety goal, stated in a more quantitative manner than fire safety goals.
Fire Safety Criteria	Performance objectives, further quantified and stated in engineering terms, relating to individual products, systems, assemblies or areas. Provides pass/fail threshold values to be compared to design evaluation output.
General Code or Standard Requirements	Provisions from the code or standard relating to the building design and construction, particularly retained prescriptive requirements.
Building Purpose and Aesthetic Goals	Building owner’s and stakeholders’ overall intentions for the building, ranging from building’s intended purpose to desired architectural plan.
Specific Code or Standard Requirements	Provisions from the code or standard directly pertaining to the occupant characteristics, assumptions, scenario data, or building characteristics. These specific requirements combine with characteristics, assumptions and scenario data specified by the design team based upon the proposed building design. These requirements for the characteristics, assumptions, and scenario data cannot be modified by the design team at any time during the evaluation.
Proposed Building Design (Including Fire Protection Design)	Building design to be evaluated by the fire protection engineer against the previously determined fire safety criteria. Initial proposal should include preliminary architectural and structural design, as well as proposed fire protection system design.
Occupant Characteristics	Ability, behavior, and vulnerability of the anticipated distribution of people before and during a specific fire scenario. Important elements include response characteristics such as sensibility and mobility, occupant location, or number of occupants. Characteristics such as number and location of occupants may be dependent on the proposed building design and the fire scenario being investigated, whereas the response characteristics and any code or standard restrained characteristics must remain the same throughout the design.
Assumptions	Specifications made by the fire protection engineer regarding the building and surrounding area, which are not part of the building design, do not vary across fire scenarios, and will be used as input to evaluate the building. Examples include emergency response or staff assistance.
Scenario Data (Including Design Fire)	Quantitative description of fire, and any factors affecting or affected by it, in the time from ignition to extinguishment, including ignition sources, ventilation, and configuration of fuel. Factors that do not vary across scenarios may be treated as assumptions. Any specific code or standard requirements for scenario data must be maintained throughout the analysis, regardless of the proposed building design. For example, building systems/features status (doors opened or closed) may be treated as a scenario factor or an assumption.

Figure A-3-2.2 Continues

Building Characteristics	Features of the building which are not specifically included in overall design, but will have an impact on overall performance, including building contents and anticipated layout. Any specific code or standard requirement for the building characteristics may not be changed at any time in the evaluation.
Design Specifications	Those aspects of the building design that will have an impact on the fire safety analysis, expressed in engineering terms. Examples include floor area and barrier layout, building height, or sprinkler density.
Input	List of all relevant design information, expressed in engineering terms, to be used in the verification method(s) to evaluate the design.
Verification Methods	Model, tool, or similar method used to evaluate the proposed design against the level of performance specified by the fire safety criteria.
Output	Specific results obtained from verification methods and design tools. Expressed in engineering terms, which can be compared directly to fire safety criteria.
Safety Factors	Adjustment factors applied to compensate for uncertainty in the assumptions, methods, and calculations employed in evaluating engineering designs.
Acceptable?	Represents comparison of output (obtained from the design evaluation) to fire safety criteria (developed by design team from code or standard and stakeholder goals) to determine if building satisfies performance requirements.
Modify Proposed Building Design	If design output fails to meet all of the fire safety criteria, modifications must be made to the preliminary design. These modifications in the proposed design could lead to changes in the design assumptions, scenario data, building characteristics, and/or design specifications, producing variations in the design input. Only those aspects of the design not specified by the code or standard may be modified, and the Technical Committee should specify which, if any, of the input values cannot be changed by the designer in order to satisfy the performance requirements.
Finish	If the design evaluation satisfies all of the fire safety criteria, then the proposed design becomes a successful trial design. After evaluating each proposed design and determining those that pass all of the fire safety criteria, the design team must select the most desirable for implementation as the final design. This final design, along with all relevant design information and data sources, must be documented in full for submittal to the AHJ for approval.

A-4-3.1 Life Safety. Examples of fire safety goals stated in terms of impact on people might be:

- (a) Assure risk of death due to fire is no higher than current level for similar properties,
- (b) Assure that anyone capable of self-evacuation and not intimate with the ignition can safely escape.

A-4-3.2 Property Protection. Examples of fire safety goals stated in terms of property protection might be:

- (a) Maintain structural stability,
- (b) Ensure that a fire remains small.

A-4-3.3 Mission Continuity. Examples of fire safety goals stated in terms of mission continuity might be:

- (a) Ensure resumption of operations as soon as possible,
- (b) Avoid a critical loss of inventory.

A-4-3.4 Environmental Consequences. Examples of environmental goals include:

- (a) Prevent the release of any radiation to the environment,
- (b) Ensure firefighting activities have a minimal environmental impact.

A-4-3.5 Heritage Preservation. Examples of heritage preservation goals are similar to property protection goals and may include:

- (a) Minimize damage to all museum galleries,
- (b) Maintain structural stability,
- (c) Ensure that a fire remains small.

A-4-3.6 Firefighter Safety. Examples of firefighter safety goals may be:

- (a) Provide adequate building/site access for firefighting apparatus and equipment,
- (b) Provide adequate information to firefighters during an emergency.

A-5.4 Performance-Based Fire Safety Objectives

As a further example of performance based objectives, consider the prototype objectives found in Appendix C of the NFPA in-house task group report, for a prototypical NFPA 13DX, *Residential Sprinkler Systems*. In this case, there are two levels of objectives; one for overall performance and another for the (sprinkler) system. The prototypical, overall performance objectives are:⁴¹

Protection of Occupants. A sprinkler system shall be designed, installed, and maintained to reduce the likelihood of instantaneous or cumulative exposure to conditions that exceed the survivability criteria of the occupants not intimate with ignition for the period of time necessary for occupant evacuation.

Prevention of Flashover. A sprinkler system shall be designed, installed, and maintained to reduce the likelihood of flashover in the room of fire origin for the period of time necessary for occupant evacuation.

The prototypical objectives for the (sprinkler) system deal with the water supply, system components (i.e., pipes, valves, etc.), design specification, testing, and repair and maintenance.

A-6-3.1 Performance Criteria Specification. As a further example of performance criteria, consider the prototype criteria found in Appendix C of the NFPA in-house task group report for a prototypical NFPA 13DX, *Residential Sprinkler Systems*. In this case there are, essentially, two performance criteria that relate to the two overall performance objectives: survivability and flashover prevention.⁴² The prototypical performance criteria for survivability are “measured” five feet above the floor and involves a consideration of the temperature and various gaseous species concentrations (e.g., CO, O₂). The flashover prevention criteria also specifies an upper layer temperature and a radiant heat flux to the floor.

A-8.1.3 Code or Standard Versus Designer Specified Characteristics.

The Technical Committee is going to have to decide which, if any, characteristics are going to be specified or constrained by the code or standard (i.e., by the AHJ) as expressions of the community’s judgement of acceptable risk. One example of this concept might include a code or standard specifying that, when analyzing an apartment complex for an egress analysis, the occupants shall all be sleeping at the time of alarm. Additional examples include a code or standard specifying a minimum number of occupants with disabilities be incorporated into the design, or an AHJ specifying that an evaluation be based on a specified degree of overcrowding, which reflects a community conservatism in requiring a robust design that is not rendered unsafe by foreseeable lapses in enforcement of operating requirements.

A-8.1.4 Characteristics Development.

Examples of characteristics that are neither dictated by the code or standard nor derived from the design include, but are not limited to, speeds of reaction and travel for occupants, and type and arrangement of fuel packages in a typical office to be considered in the design as an area of origin. The Technical Committee must ensure that the design team uses safe, conservative values for their selection of characteristic values. Failure to use or consider conservative values for characteristics is the same as making a value judgement that the loss of vulnerable people or the loss of everyone when the building is not in ideal condition are acceptable losses for the community.

A-8-2.3 Response.

The design team should focus on the four main response characteristics when developing the occupant characteristics. These occupant performance characteristics can be further separated into those presented in the table below.

Table A-8-2.3

Occupant Performance Characteristic	Description
Alertness	Are occupants awake or asleep? Dependent on time of day.
Location	Where are the occupants in relation to alarm cues and escape routes?
Responsiveness	What are occupants' abilities to sense and react to cues?
Commitment	To what degree are the occupants committed to the activity that they are performing at the time of alarm?
Focal Point	What are the occupants focusing on at the time of the alarm (Front of classroom or stage, movie screen)?
Physical and Mental Capabilities	What are the abilities of the occupants to sense, respond, and react to cues? Are the occupants impaired or disabled?
Role	What role will the occupant play in the building evacuation? Leader or follower, staff or person in need of help?
Familiarity	How familiar are the occupants with the building? How much time have they spent in the building and have they performed any emergency training?
Social Affiliation	To what extent will the occupants act/react as individuals? What affect will social psychology have? Will group dynamics play a role?
Number of Occupants	How many occupants are located in the building, and how are they distributed? What affect will time of day and month of the year have on this number?
Condition	What will the physiological and psychological effects of the fire be on the occupants throughout the course of the fire.

A-8-3.1 Definition. The building characteristics include not just the building, but also that which is located inside the building. In addition to the human occupants, the Technical Committee may have to consider a particular area or process within the building that must be protected and given special consideration. As an example, a semiconductor manufacturing facility's primary interest is to protect the manufacturing process and clean rooms, preventing any products of combustion from entering rooms and spaces outside of the area of origin. In most cases, these processes are either far more susceptible to damage from minor quantities of smoke and products of combustion than any human occupants, represent a significant hazard to the occupants, or are critical to mission continuity (i.e., facility operation). If the goals, objectives, and criteria target specialized areas or processes, then the design team must specify the characteristics of these areas or processes, which can then be used as input for the evaluation. Included in these characteristics should be the anticipated location and distribution, as well as the overall susceptibility, of these specialized areas and processes. The susceptibility terms could include, but are not limited to, smoke concentration

(parts per million), incident heat flux (kW/m²), or maximum permissible shell temperature of a storage vessel (°C).

Additionally, the Technical Committee must remember that this document uses the term building to indicate the topic of the code or standard in question. Therefore, the building characteristics shall be specified or developed based upon whatever type of structure, component, system, etc., is covered by the scope of the code or standard under consideration.

A-8-3.3 Building Contents. Examples of the characteristics for the building contents and furnishings that could be reported in a submittal to the AHJ include, but are not limited to, the fuel load, burning properties of materials and products, placement and geometry considerations, and special product conditions such as changes in burning properties due to aging or vandalism. Much of this information could be listed with the assumptions, and the Technical Committee should state where the information should be included in the submittal if required.

A-9-5.1 Emergency Response. Any information regarding the speed of response, effectiveness, anticipated roles, and other important characteristics of the emergency personnel should be specified or estimated.

A-9-5.2 Staff Assistance. The reasoning behind the requirements for staff assistance should be outlined in the standard. If the design team incorporates staff assistance into the analysis, they must state the staff qualifications, how many people will be available, how they are going to be deployed, what they are going to be doing, etc. The design team must present engineering calculations or credible reference data supporting their assumptions regarding staff assistance to the AHJ.

A-9-5.3 Off-site Conditions. If the design team anticipates that offsite conditions might affect the building performance, then the condition in question should be specified as part of the design. An example would include the location and condition of the water main that the designer intends to use as the water supply for a sprinkler system.

A-9-6 Building Features and System Performance. If the building features and systems are installed according to NFPA standards, then the reliability of these components can generally be assumed to be 100%, with the exception of those scenarios that explicitly state that the analysis should consider an impaired or non-operational system. If the Technical Committee feels a lower overall reliability should be used in the design, then that value, or a method to determine this reliability, should be distinctly stated or specified.

A-10-4 Consistency. To thoroughly evaluate the scenarios it may be helpful to use a flow chart or concept tree to follow the performance-based design process in an organized manner. NFPA 550, *Guide to the Fire Safety Concepts Tree*, might be a useful tool to achieve consistency.⁴³

A-10-6-1 General. One must be careful to remain realistic when selecting scenarios. It is easy to be under or overly conservative; a balance must be found. For example, it would be devastating if a meteor hit the building in question, but is that realistic? Is that a problem any building is likely to face in its lifetime? Obviously not; therefore, there is no need to provide protection for the building and its occupants in that situation.

Is it possible that a building is a target for terrorist activity (e.g., bomb, arson)? That is more likely than a meteor, but how severe an incident is likely enough to be used for planning?

On the opposite side of the spectrum, there is a very good chance that a fire could block the most commonly used means of egress, therefore, this possibility should be incorporated into the design analysis.

A-10-6.3 Level of Acceptable Loss. The design fire scenarios, along with the performance criteria, provide the most ideal place for the Technical Committee to quantify acceptable levels of safety and risk.

Included below are excerpts from NFPA 805, *Performance-Based Fire Protection for Light Water Reactor Electric Generating Plants*.⁴⁴ These excerpts were included so that the Technical Committee may get a general idea of how one committee addresses acceptable loss. These sections outlines very general criteria, as this standard relies upon the user to expand on their detail.

1-4.4 Plant Damage/Business Interruption Objectives. In order to meet the plant damage/business interruptions goals, the following objectives shall be met during all operational modes and plant configurations:

- (1) Potential property damage due to fire shall be limited to an acceptable level as determine by the owner/operator.
- (2) Potential business interruption (plant downtime) due to fire shall be limited to an acceptable level as determine by the owner/operator.

1-5.1 Nuclear Safety Performance Criteria. Fire protection features shall be capable of providing reasonable assurance that, in the event of a fire, the plant is not placed in an unrecoverable condition. To demonstrate this, the following performance criteria shall be met:

- (a) *Reactivity Control*. Shall be capable of inserting negative reactivity to achieve and maintain subcritical conditions. Negative reactivity inserting shall occur rapidly enough such that fuel design limits are not exceeded.
- (b) *Inventory and Pressure Control*. Shall be capable of controlling coolant level such that subcooling is maintained for a PWR and shall be capable of maintaining or rapidly restoring reactor water level above top of active fuel for a BWR.
- (c) *Decay Heat Removal*. Shall be capable of removing sufficient heat from the reactor core or spent fuel such that fuel is maintained in a safe and stable condition.
- (d) *Vital Auxiliaries*. Shall be capable of providing the necessary auxiliary support equipment and systems to assure that the systems required under (a), (b), (c), and (e) are capable of performing their required nuclear safety function.
- (e) *Process Monitoring*. Shall be capable of providing the necessary indication to assure the criteria addressed in (a) through (d) have been achieved and are being maintained.

1-5.2 Radioactive Release Performance Criteria. Radiation release due to the direct effects of fire, or fire suppression activities (but not involving fuel damage) shall be as low as reasonably achievable and shall not exceed 0.002 rem (0.02 millisevert) in any one hour.

1-5.3 Life Safety Criteria. The following performance criteria shall be met during all operational modes and plant configurations:

- (1) Provide safe egress and/or area of refuge for occupants other than essential personnel.
- (2) Provide adequate protection, including emergency lighting, for essential personnel to perform necessary safety functions as a result of a fire event.

- (3) Provide adequate protection for essential personnel, providing necessary emergency services during or following a fire.

1-5.4 Plant Damage/Business Interruption Criteria. In order to meet the individual plant damage/business interruption objectives, the following criteria shall be satisfied as described below.

- (a) The probable maximum loss (PML) shall not exceed an acceptable level as determined by the owner/operator.
- (b) The business interruption (plant downtime) due to a PML fire event shall not exceed an acceptable level as determined by the owner/operator.

A-1-5.4 Determination of the acceptable levels of damage and downtime for systems and structures that are not related to nuclear safety and that do not impact the plant's ability to achieve the nuclear safety criteria is largely a matter of economics. These values will be site-specific based on financial criteria established by the owner/operator. The owner/operator's analysis should consider factors such as the cost of installing and maintaining protection, the potential damage from the hazard or exposures (combustible load), the replacement cost of damaged equipment, and the downtime associated with replacement/repair of damaged equipment. Risk-informed data for the frequency of ignition sources, transient combustibles, or fire associated with the hazard should be considered.

A-10-6.5 Key Characteristics in Design Fire Scenarios. Providing core scenarios in an NFPA document is meant to limit a designer's performance options to those that will provide acceptable safety against all fires society expects a building to handle. A proper engineering analysis cannot be performed without considering certain scenarios. It may not be necessary to use every core scenario, but a compelling reason for not incorporating a scenario

must be given, based on hard evidence, and be well documented in the design report.

The eight scenarios presented below are the scenarios found in NFPA 101, *The Life Safety Code*.⁴⁵ It is understood that these specific scenarios may not be pertinent to the focus of each code and standard; however, each scenario addresses specific issues that are of importance to many Technical Committees, which is why they are presented in this Primer. Each Technical Committee should be encouraged to develop those scenarios it feels are necessary.

Design Fire Scenario 1. An occupancy-specific design fire scenario representative of a typical fire for the occupancy. This design fire scenario shall explicitly account for: occupant activities, number and location; room size; furnishings and contents; fuel properties and ignition sources; and ventilation conditions. The first item ignited and its location shall be explicitly defined.

Design Fire Scenario 2. An ultrafast-developing fire, in the primary means of egress, with interior doors open at the start of the fire. This design fire scenario shall address the concern of reducing the number of available means of egress.

Design Fire Scenario 3. A fire, starting in a normally unoccupied room, that can potentially endanger a large number of occupants in a large room or other area. This design fire scenario shall address the concern of a fire starting in a normally unoccupied room and migrating into the space that can, potentially, hold the greatest number of occupants in the building.

Design Fire Scenario 4. A fire originating in a concealed wall- or ceiling-space adjacent to a large occupied room. This design fire scenario shall address the concern of a fire originating in a concealed space that does not have either a detection system or suppression system, and the fire spreading into the room within the building that can, potentially, hold the greatest number of occupants.

Design Fire Scenario 5. A slowly developing fire, shielded from fire protection systems, in close proximity to a high occupancy area. This design fire scenario shall address the concern of a relatively small ignition source causing a significant fire.

Design Fire Scenario 6. The most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building. This design fire scenario shall address the concern of a rapidly developing fire with occupants present.

Design Fire Scenario 7. Outside exposure fire. This design fire scenario shall address the concern of a fire starting remotely from the area of concern and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area.

Design Fire Scenario 8. A fire originating in ordinary combustibles in a room or area with each passive or active fire protection system rendered – one by one – unavailable. This set of design fire scenarios shall address the concern of each fire protection system or fire protection feature, considered individually, being unreliable or unavailable.

The proposed NFPA 101 uses the approach of defining eight scenarios that the TC felt adequately challenges a fire protection design. NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants* presents the use of scenarios in a somewhat different way. After defining an area of origin and its characteristics (e.g., geometry, vent configuration, potential fuel load etc.), the designer would test the design under the conditions listed below.⁴⁶

- (a) Fire with all existing fire protection features in place and operating. This includes assumptions that the automatic suppression system, where existing, will control and extinguish the fire.
- (b) Same fire as (a) with assumption that the automatic suppression system will control fire growth but not extinguish the fire.
- (c) Same fire as (a) with assumption that the suppression system will not operate.
- (d) Same fire as (a) with assumption of single failure of a fire protection system or feature, other than automatic suppression, as may be applicable:

- (1) Failure to operate smoke control system.
 - (2) Failure of water supply to hose connections.
 - (3) Failure to operate heat actuated opening protective device (e.g., fire damper, water curtain, held-open door).
 - (4) Failure of room enclosure (e.g., open door, broken glazing).
- (e) Same fire as in (b) with assumption of single failure of a fire protection system or feature, other than automatic suppression as may be applicable:
- (4) Failure to operate smoke control system.
 - (2) Failure of water supply to hose connections.
 - (3) Failure to operate heat actuated opening protective device (e.g., fire damper, water curtain, held-open door).
 - (4) Failure of room enclosure (e.g., open door, broken glazing).

Some of the above combinations constitute envelope conditions for other scenarios, so that not all scenarios need to be modeled in all cases. If it can be determined that the probability of a particular scenario occurring is 1×10^{-6} , then that one can be disregarded.

An acceptable design should afford safe conditions under scenarios (a) and (b), as well as under any of the single failure scenarios of (d). It is desirable, but not required that designs pass single system failure scenarios listed under (e) but failure does not necessarily preclude acceptability of the design.

A-10-7.4 Data Use. Use of percentages to choose likely scenarios is not as easy as it sounds. Judgment is involved in selecting the categories that define alternative scenarios.

First, remember that the dimensions and factors used to code and describe historical fires in available data bases are not always the same dimensions and factors required as input data for a fire hazard analysis model. A translation is required, and every translation involves an assumed or demonstrated relationship between fire experience data characteristics and desired input data characteristics.

It is essential that these relationships be substantiated as much as possible.

For example, it would not be valid to assume that all arson fires are fast or severe fires (i.e., have a steeply rising rate of heat release or a high peak rate of heat release). Most arson fires do not involve the use of accelerants and are started by juveniles, not by individuals sophisticated in fire. For scenario purposes in a fire hazard analysis, the typical arson fire may behave like an ordinary trash fire. By contrast, it would be valid to assume that all fires starting with ignition of flammable liquids, whether accidental or deliberate, show the heat release rate curves associated with those products.

Second, when selecting likely scenarios, the analyst would like to identify scenarios that collectively account for a large share, preferably most, of the relevant fires. However, fire hazard analysis calculations typically require input data with so many characteristics defined that no one scenario can be expected to account for more than a tiny percentage of total fires. In such a situation, the selection of scenarios should be done in two stages. The first stage would be partitioning all the fires that can occur into a manageable number of relatively homogeneous scenario classes. A scenario class would be a group of similar scenarios that are expected or known to yield similar severity's when they occur. The second stage consists of selecting a typical fire within the class to represent the scenario class.

In a typical building, a manageable scenario class for analyzing home fires might consist of all fires originating in ordinary combustibles in any room that people normally occupy, i.e., excluding means of egress that people pass through but do not normally stay in and excluding service areas and concealed spaces. Then, the representative fire within the class might be an upholstered furniture fire within a living room. That is not necessarily the most likely scenario within the class (kitchen fires involving food on a stove are more common, for example), but it is a very common scenario that is easier to quantify for analysis purposes, given existing laboratory data, and is probably more typical of the fires in the class.

As the examples cited earlier suggest, high-challenge scenarios can often be defined in terms of an area of origin and a fire size, both of which are dimensions that can be assessed statistically and used as engineering specifications for an engineering analysis of a building. Other appropriate dimensions to use in

defining high-challenge scenarios would include time of day (an indicator of the status of occupants).

It is possible that the fire protection design is intended to prevent fires from ever growing to the design fire size being considered. In this, assuming such a fire size would force the analyst to assume failure of any design features intended to prevent growth of the fire to the designated fire size. This in turn could show the overall design to be unacceptable when such was not the case. A high-challenge scenario could instead be defined in terms of an initial fuel package that (a) statistics show to be high-ranking in terms of probability and associated with a high rate of deaths per fire, and (b) engineering data shown to be associated with a high peak rate of heat release and a high rate of heat release. This will produce a fire tending to become severe quickly and will therefore be a good high-challenge test of the design but without prejudging the effectiveness of design elements intended to act early in the fire.

Three major data bases are available to analyze patterns in U.S. fire experience -- the annual NFPA survey of fire departments; the FEMA/USFA National Fire Incident Reporting System (NFIRS); and the NFPA Fire Incident Data Organization (FIDO). Together, these three data bases can provide valid, detailed information that is the best basis in the USA for constructing fire scenarios.

Annual NFPA Survey of Fire Departments

The NFPA survey is based on a stratified random sample of roughly 3,000 US fire departments (or roughly one of every ten fire departments in the country). The survey collects the following information that may be useful in fire hazard calculations: the total number of fire incidents, civilian deaths, and civilian injuries and the total estimated property damage (in dollars) for each of the major property-use classes defined by the NFPA 901 standard for fire incident reporting.⁴⁷ These totals are analyzed and reported in NFPA's annual study, "Fire Loss in the United States," which traditionally appears in the September/October issue of *NFPA Journal*.

The NFPA survey is stratified by size of population protected to reduce the uncertainty of the final estimate. Small, rural communities protect fewer people per department and are less likely to respond to the survey, so a larger number must be surveyed to obtain an adequate sample of those departments.

NFPA also makes follow-up calls to a sample of the smaller fire departments that do not respond, to confirm that those that did respond are truly representative of fire departments their size. On the other hand, large city departments are so few in number and protect such a large proportion of the population that it makes sense to survey all of them. Most respond, resulting in excellent precision for their part of the final estimate.

These methods have been used in the NFPA survey since 1977 and represent a state-of-the-art approach to sample surveying. Because of the attention paid to representativeness and appropriate weighting formulas for projecting national estimates, the NFPA survey provides a valid basis for measuring national trends in fire incidents, civilian deaths and injuries, and direct property loss, as well as for determining patterns and trends by community size and major region.

FEMA/USFA's National Fire Incident Reporting System (NFIRS)

The Federal Emergency Management Agency's US Fire Administration (FEMA/USFA) administers and distributes NFIRS, an annual computerized data base of fire incidents, with data classified according to a standard format based on NFPA 901. Roughly three-fourths of all states have NFIRS coordinators, who receive fire incident data from participating fire departments and combine the data into a state data base. This data is then transmitted to FEMA/USFA. (To obtain a copy of the NFIRS data tape for a particular year, contact the National Fire Data Center, U.S. Fire Administration, 16825 South Seton Avenue, Emmitsburg, MD 21727-8995, or call 301-447-6771.) Participation by the states, and by local fire departments within participating states, is voluntary. NFIRS captures roughly one-third to one-half of all US fires each year. A larger proportion of US fire departments are listed as participants in NFIRS, but not all departments provide data every year.

NFIRS provides the most detailed incident information of any reasonably representative national data base not limited to large fires. NFIRS is the only data base capable of addressing national patterns for fires of all sizes by specific property use and specific fire cause. (The NFPA survey separates fewer than twenty of the hundreds of property use categories defined by NFPA 901 and provides no cause-related information except for incendiary and

suspicious fires.) NFIRS also captures information on the construction type of the involved building, height of building, extent of flame spread and smoke spread (which are useful in estimating whether flashover occurred and whether conditions would have caused an operational smoke detector to operate, respectively), performance of detectors and sprinklers, and victim characteristics, the latter in individual casualty reports which accompany the incident reports in an NFIRS file.

One weakness of NFIRS is that its voluntary character produces annual samples of shifting composition. Despite the fact that NFIRS draws on three times as many fire departments as the NFPA survey, the NFPA survey is more suitable as a basis for projecting national estimates because its sample is truly random and is systematically stratified to be representative.

Most analysts use NFIRS to calculate percentages (e.g., the percentage of residential fires that occur in apartments, or the percentage of apartment fire deaths that involve discarded cigarettes), which are then combined with NFPA-survey-based totals, to produce estimates of numbers of fires, deaths, injuries, and dollar loss for subparts of the fire problem. This is the simplest approach now available to compensate in the area where NFIRS is weak. It has been documented as an analysis method in a 1987 article in *Fire Technology*.⁴⁸

NFPA's Fire Incident Data Organization (FIDO)

NFPA's FIDO is a computerized index and data base that provides the most detailed incident information available, short of a full-scale fire investigation. The fires covered are those deemed by NFPA to be of major technical interest. The tracking system that identifies fires for inclusion in FIDO is believed to provide virtually complete coverage of incidents reported to fire departments involving three or more civilian deaths, one or more fire fighter deaths, or large dollar loss (redefined periodically to reflect the effects of inflation, and defined since the late 1980s as \$5,000,000 or more in direct property damage).

FIDO covers fires from 1971 to date, contains information on more than 70,000 fires, and adds about 2,000 fires per year. NFPA learns of fires that may be candidates for FIDO through a newspaper-clipping service, insurers' reports, state fire marshals, NFIRS, responses to the NFPA annual survey, and other sources. Once notified of a candidate fire,

NFPA seeks standardized incident information from the responsible fire department and solicits copies of other reports prepared by concerned parties, such as the fire department's own incident report and results of any investigations.

The strength of FIDO is its depth of detail on individual incidents. Coded information that may be captured by FIDO, but never by NFIRS, includes detailed types and performance of built-in systems for detection, suppression, and control of smoke and flame; detailed factors contributing to flame and smoke spread; estimates of time between major events in fire development (e.g., ignition to detection, detection to alarm); reasons for unusual delay at various points; indirect loss and detailed breakdowns of direct loss; and escapes, rescues, and numbers of occupants. Additional uncoded information often is available in the hard-copy files, which are indexed by FIDO for use in research and analysis.

FIDO is a resource that may be used with NFIRS-based national estimates in the same manner that NFIRS is used with the NFPA survey to produce national estimates. That is, a FIDO analysis may provide reasonable estimates of how a block of fires, estimated through NFIRS-based national estimates, further subdivides into more detailed categories.

Neither FIDO nor any other special fire incident data base with detail exceeding that in NFIRS is directly available to analysts outside the organization that maintains the data base. It will be necessary to arrange with analysts in charge of the data base to obtain needed analyses, and at that time, the data base analysts can help indicate what analyses are possible with the data.

Working with the Strengths and Weaknesses of Different Data Bases

No fire data base can possibly capture all instances of unwanted fires. Few data bases cover fires that are not reported to fire departments. By their nature, fire data bases are biased in favor of "failures" rather than "successes." The fire that is controlled so quickly it does not need to be reported to a fire department is not captured by the data bases that cover reported fires. Analyses of the impact of devices and procedures that provide early detection or suppression also need to allow for the phenomenon of missing "success" stories.

There is also the issue of quality control for a data base. For data bases with limited depth of detail (like the NFPA survey) or limited breadth of coverage (like FIDO, which is primarily devoted to large fires), it is possible to invest considerable effort in ensuring that each report is as complete and accurate as possible. Follow-up calls can be used to fill gaps and check possible odd answers. For a data base with the depth and breadth of NFIRS, however, the same level of quality control effort has not been possible. Consequently, NFIRS is missing more entries and has more that are dubious. The trade-off between data quality and data quantity is never easy; an analyst needs to be aware of the strengths and limitations of the sources before conducting an analysis.

A-11-1.3 Verification Methods. It is important to note that using a verification method is not as simple as inputting a value, executing the method, and getting an answer. The results obtained from a verification method are not the only answer to a problem. More often the results obtained from one tool are used as input into another. It cannot be stressed enough that this phase of the PB process is highly iterative and complex.

A-11-1.4 Selection. Because of the specified scope of some of the Technical Committee's codes or standards, there may not be a verification method listed in this document or currently available in the field that suits the needs of these special issues. The best solution may be a creative mix of solution methods.

A-11-1.4.2 Verify. When verifying a design, it is important to be as accurate as possible. For this reason more than one method should be applied to the design, several times each, to establish a range of results. The Technical Committee may wish to stress that the designer run multiple runs with the verification method chosen to analyze the design, with these results supported by the results of at least one additional design tool. This additional design tool may be as simple as a set of fundamental hand calculation that will yield a rough approximation of the desired results, and provide the designer and the AHJ with the assurance that the model results are physically reasonable.

A-11-2.2 Limitations. The more sophisticated a tool (i.e., computer models) is, the more assumptions and simplifications the tool will be based on. Because of this, misuse of the tool by an inexperienced user is

more probable (although all users are susceptible to misuse). Proficiency in using sophisticated tools, like computer models, comes with experience. Other Technical Committees, already considering a PB approach, have decided that the level of experience of the designer is an important factor in the verification process and have required it be documented in the proposed solution to the AHJ.

A-11-2.3.2 Physics Models. Raymond Friedman wrote an overview of various computer fire and evacuation models and issues to consider when using these tools.⁴⁹ The article focuses more on fire models than evacuation models but serves as a good reference to better understand the issues surrounding the use of computer models in a fire scenario analysis.

The Fire Protection Handbook, Section 11, Chapters 4 and 5 can also be referenced.

A-11-2.3.2.1 Field Models. Typically, field models are expensive to purchase, have a steep learning curve, and may take hours or days to run a single scenario (depending on the complexity of the geometry). They are more likely to explicitly model combustion, but usually still rely on a user specified fire.

A-11-2.3.2.3 Purpose Built Models. Zone models can predict flows into and out of rooms, heat transfer to enclosure surfaces and convection out of the room, time to ignite a second item, plume flow, gas temperatures under the ceiling, etc. Purpose built models may predict a single component or value of interest, e.g., only gas temperature, only the time at which a window breaks, or only the upper layer temperature. An example of their use might be to predict the ceiling jet temperature at a specified distance from the center of a fire plume, e.g. the approximate distance to a sprinkler head, in order to estimate the time to activation of that sprinkler.

A-11-2.3.6 Non-Fire Models. An example of a non-fire or evacuation model that may be required in a performance-based code may include a computer model of a plume dispersions from a ruptured pipe or fuel spill. This type of model might be used in the design of an industrial facility in order to determine the time until a gaseous fuel source might ignite, or the percentage of toxic substances at different distances from the source.

A-11-2.4.2 Experimental Data. Experiments are typically carried out to explore the effect on the outcome due to variations in different aspects of a scenario. The key to using experimental data as a verification method for a specific scenario is determining how similar is similar enough e.g. how much different can the experiment be from the actual situation which is being modeled with the verification method.

A-11-2.4.5 Start-up Tests. The start-up test is defined as the initial operation of a system, immediately after system completion/installation; i.e., an in situ commissioning test.

A-11-2.5 Probabilistic Tools. The following sources contain information on various probabilistic tools. This list is a point of reference and not complete. It should not limit the use of other probabilistic tools:

-The SFPE Handbook of Fire Protection Engineering⁵⁰

- Section 1 / Chapter 11, 12
- Section 3 / Chapter 15
- Section 5 / Chapters 2,3,4,10,11,12

- The Fire Protection Handbook⁵¹

- Section 11 Chapter 6, 8 11

- NFPA 101A - Alternative Approaches to Life Safety⁵²

A-11-2.5.2 Probabilistic Tree Model. Computer programs that can solve both failure and event trees are available. Such computer programs will allow the user to quickly and easily determine the likelihood of success or failure of a top event, or the likelihood of a particular event occurring. Additionally, these programs will allow the user to determine the level of uncertainty associated with these likelihood values. The benefit of these programs is their ability to quickly determine the probability or frequency values, allowing the designer to analyze multiple runs without having to calculate out the full solution for each run.

A-11-2.6 Heuristic Tools. A heuristic tool is one that can be easily manipulated to produce misleading results. Although these tools can be applied following scientific methodology, they are not mathematically based, therefore, reproducing the results of one designer by another is not likely.

Heuristic tools should be used in conjunction with deterministic or probabilistic tools.

A-12-3.1 Conservative Values. The design team should ensure that properly conservative values are used as input to the verification method. However, the designer must be careful that the use of overly conservative values in one aspect of the design does not lead to a lack of conservatism in another. One example would be a conservative estimation of the fire size in order to determine the time to failure of the steel members in the building, without considering the impact this fire will have on possibly decreasing the time to detection and agent application.

A-12-3.2 Sensitivity Analysis. Typical examples of parameters whose values might be varied in a sensitivity analysis include cubicle arrangement in an office building, status of doors, time to occupant movement following an alarm, and ventilation characteristics.

A-12-3.3 Safety Factors for Design Variables. Safety Factors can be applied at almost any stage of the analysis. If the Technical Committee specified that a safety factor of 2 be applied directly to the design output, then one example of its application could be to double the evacuation time in a egress analysis. However, if the safety factor is to be applied in the design input stage, then the design team must ensure that this application non-conservative results for any aspects of the design. For example, if the user wanted to determine a conservative estimate of time to failure of steel beams of a ceiling, a factor could be applied to increase the fire growth rate. While this would produce conservative estimates of the time to steel failure, the estimates for time to sprinkler activation would not be conservative due to the overestimation of the fire growth, and a separate analysis would have to be completed to determine this value.

A-13-2.2 NFPA Context. In the context of NFPA codes and standards, there are two types of reliability, operational and performance. Each of these components may be illustrated with fire pumps. First, the fire pump must start when commanded to do so (operational reliability). Second, the pump must provide a specified pressure and flow for a specified period of time or otherwise effectively perform its mission as designed (performance reliability).

A-13-3.1 Equipment vs. Human Reliability.

Reliability is not entirely, or even primarily, about mechanical or electrical reliability, as quite frequently human error will lead to partial or total failure of a feature or system. Shutting off the main sprinkler valve for maintenance and not remembering to turn it back on is an example related to active suppression systems. Disabling a home smoke alarm because of frustration over nuisance alarms is an example related to active detection/alarm systems. Blocking doors open or poking holes in walls are examples related to passive protection features. Failure of staff to perform their designated roles in containing fires or supporting evacuation is an example related to assigned roles of people in support of the design.

A-13-3.4.5 Addressing Reliability Through Factors of Safety.

As an example of how one must be careful when trying to use safety factors to address reliability, suppose a hotel design is being evaluated for its ability to protect guests from a couch fire in the lobby. There is uncertainty involved in measuring the actual burning properties of the couch. There is uncertainty in the characterization of air flow and of other physical characteristics of the room of fire origin. And the calculation method used to estimate the development of fire hazard may introduce modeling uncertainties. All these sources of uncertainty can be studied in an uncertainty or sensitivity analysis and can be offset by safety factors defined as multipliers on fire severity or on the time required to reach certain stages of fire development, as discussed in Chapter 12. But they are not the same concerns as the possibility that the detection/alarm or sprinkler system will be disabled when the fire begins, that doors to the lobby will be blocked open, or that staff will fail to react as they are expected to react.

A-14-2 Design Report Layout. The Technical Committee should provide guidance and requirements regarding the layout and content of the design report. The table below provides an example of the content and layout of a design report, and can be used by the Technical Committee to develop requirements and guidance for the code or standard in question.

Table A-14-2. Sample Report Layout

Section Number	Section Content
1	Presentation of project scope, including a summary of building’s purpose and aesthetic goals
2	Summation of engineer/design team capabilities, including but not limited to a resume and any other information supporting the engineer’s qualifications relating to performance-based design.
3	Code or standard specified goals and objectives, along with performance criteria either specified in code or standard or developed by design team based on goals and objectives.
4	Final fire protection system design summary. Description of system as a whole, as well as description and installation instructions for each individual component.
5	Description of each fire scenario to which the building design was exposed. Include in this section a description of each scenario, why it was chosen, and how design fires can be extrapolated from each fire scenario.
6	Design input, separated into the building characteristics, assumptions, occupant characteristics, building specifications, and design fires. Each of these components of the input data shall be listed separately, with references provided for the characteristics and assumptions, and reference to the previous sections provided for the building specifications and each design fire. Additional data on the building and occupant characteristics, assumptions, building specification, and design fire scenarios not used as input but still relevant to the design should be included in this section but listed separately from the design input.
7	Information on the verification methods used in the design, including a detailed description of the design tools, a justification of the models’ applicability, and documentation of the modelers’ capabilities.
8	Base case design output before application of safety factor or sensitivity analysis. Safety factor and justification for its value. Base case design output with safety factor applied. Various design output results after various sensitivity analysis, with description of each variable modified.
9	Summary of design acceptance via comparison of design output to performance criteria. Note allowable range of input variables from sensitivity analysis presented in previous section.
10	References used in the preparation of the design should be included. Copies of specific references which are either proprietary, difficult to obtain, or part of the operations and maintenance of the building or design, should be included in the submittal
11	Design appendices, as described in the ensuing sections of this document.

Appendix B - Reference Publications

This Appendix is not part of the recommendations of this NFPA document, but is included for information purposes only.

¹ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

² *Bottom-Up Analysis of National Code*, Canadian Codes Centre, September 1996.

³ *Bottom-Up Analysis of National Code*, Canadian Codes Centre, September 1996.

⁴ *Bottom-Up Analysis of National Code*, Canadian Codes Centre, September 1996

⁵ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

⁶ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

⁷ Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*, Society of Fire Protection Engineers and National Fire Protection Association, 1997.

⁸ Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*

⁹ NFPA 550, *Guide to the Fire Safety Concepts Tree*, 1995 Edition.

¹⁰ *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*, Society of Fire Protection Engineers and National Fire Protection Association, 1998.

¹¹ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

¹² Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*

¹³ Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*.

¹⁴ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

¹⁵ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

¹⁶ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

¹⁷ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

¹⁸ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.

¹⁹ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

²⁰ NFPA 101, *Life Safety Code*, 2000 Edition.

²¹ Hall, John R. Jr., "Fire Risk Analysis," *Fire Protection Handbook*, 18th Edition, NFPA, 1997. Pp. 11-78 – 11 88.

²² NFPA 101, *Life Safety Code*, 2000 Edition.

²³ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

²⁴ *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, NFPA, Quincy, MA 1995.

²⁵ *NFPA Fire Protection Handbook*, 18th Edition, NFPA, Quincy, MA, 1997.

²⁶ Friedman, R., *Survey of Computer Models for Fire and Smoke*, 2nd Edition, Factory Mutual Research Corporation, Norwood, MA, 1991.

²⁷ *Computer Software Directory*, Society of Fire Protection Engineers, Bethesda, MD, 1994

²⁸ <http://www.bfrl.nist.gov/forum.html> – Forum for International Cooperation in Fire Research – International Survey of Fire Models.

²⁹ Interflam 96 – Seventh International Fire Science and Engineering Conference. St. John's College, Cambridge, England. March 1996.

³⁰ First International Symposium – Human Behavior in Fire. University of Ulster, Ireland. September 1998.

³¹ Proceedings of the Fifth International Symposium – Fire Safety Science. International Association of Fire Safety Science. Melbourne, Australia. March 1997.

³² Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*.

³³ Custer, Richard L.P. and Meacham, Brian J., *Introduction to Performance-Based Fire Safety*.

³⁴ *The American Heritage College Dictionary*, 3rd ed., Houghton Mifflin Co., Boston, 1993.

³⁵ NFPA 101, *Life Safety Code*, 2000 Edition.

³⁶ *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*, Society of Fire Protection Engineers and National Fire Protection Association, 1998.

³⁷ *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*, Society of Fire Protection Engineers and National Fire Protection Association, 1998.

³⁸ *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Building*, Society of Fire Protection Engineers and National Fire Protection Association, 1998.

³⁹ NFPA 92B, *Guide for Smoke Management Systems in malls, Atria, and Large Areas*, 1995 Edition

⁴⁰ NFPA 101, *Life Safety Code*, 2000 Edition.

-
- ⁴¹ *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.
- ⁴² *NFPA's Future in Performance-Based Codes and Standards*, National Fire Protection Association, Quincy, MA, July 1995.
- ⁴³ NFPA 550, *Guide to the Fire Safety Concepts Tree*, 1995 Edition.
- ⁴⁴ NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*. Draft 7.0 for 2000 Edition, December, 1999.
- ⁴⁵ NFPA 101, *Life Safety Code*, 2000 Edition.
- ⁴⁶ NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*. Pre-ROP Drafts for 2000 Edition, June, 1998.
- ⁴⁷ NFPA 901, *Uniform Coding for Fire Protection*, 1976 Edition (Used in most fire data bases) and 1991 Edition.
- ⁴⁸ Hall, J.R., Jr., and Harwood, Beatrice, "The National Estimates Approach to U.S. Fire Statistics," *Fire Technology*, Vol. 25, No. 2, May 1989, pp. 99-113.
- ⁴⁹ Friedman, Richard. "An International Survey of Computer Models for Fire and Smoke", *Journal of Fire Protection Engineering*, Vol. 4, No. 3, 1992, pp. 81-92.
- ⁵⁰ *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, NFPA, Quincy, MA 1995.
- ⁵¹ *The Fire Protection Handbook*, 18th Edition, NFPA, Quincy, MA 1997.
- ⁵² NFPA 101A, *Alternative Approaches to Life Safety*, 1995 Edition.