Building Fire Risk Analysis

75

Brian J. Meacham, David Charters, Peter Johnson, and Matthew Salisbury

Introduction

The aim of building fire risk analysis is to gain insight into and characterize fire-related risks to better inform the wide range of decisions that must be made as part of building design, construction, and operation. As used in this chapter, risk is defined as the possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors: loss of or harm to something that is valued, the event or hazard that may occasion the loss or harm, and a judgment about the likelihood that the loss or harm will occur [1]. Specifically, fire risk is the possibility of an unwanted outcome in an uncertain situation, where fire is the hazard that may induce the loss or harm to that which is valued (e.g., life, property, business continuity, heritage, the environment, or some combination of these). Building fire risk analysis, then, is the process of understanding and characterizing the fire hazard(s) in a building, the unwanted outcomes (relevant losses or harm) that may result from a fire, and the likelihood of fire and unwanted outcomes occurring.

Building fire risk analysis must consider several factors. Some of these factors are familiar to fire protection engineers and some perhaps are not. For example, building fire risk analysis should consider (1) what the fire hazards are and how fires might occur; (2) how the unwanted outcomes (consequences) are valued and by whom (including offsetting benefits); (3) what differences in risk perception and valuation exist and how they should be treated (i.e., should high-consequence events be disregarded if the probability of occurrence is very low); (4) if there are any social or cultural issues that may be relevant; (5) if there are different stakeholder views on the likelihood of fire occurrence and of the resulting consequences; and (6) whether uncertainty, variability, and unknowns have been identified and appropriately addressed.

Evaluation of fire hazards is something that many (or generally) fire protection engineers do well, and for which numerous tools and methods exist (e.g., this handbook). The valuation of consequences, however, requires data, tools, and methods that differ from those used for fire hazard assessment. Valuation of consequences requires consideration of physical, economic, health, environmental, social, cultural, and psychological factors. In valuing life safety consequences, for example, many engineers consider only injury and loss of life to an individual. However, there are also such factors as reduced quality of life, the inability to continue to work, and the impact on family relationships. On property protection, factors such as smoke and water damage should be considered, in addition to thermal damage. On business continuity, there are long-term issues, such as loss of image and market share, in addition to the short-term monetary losses associated with downtime.

B.J. Meacham (✉) • D. Charters • P. Johnson
M. Salisbury

M. Hurley (ed.), *SFPE Handbook of Fire Protection Engineering*,
DOI 10.1007/978-1-4939-2565-0_75,

Much like the valuation of consequences, the issue of determining the likelihood of fire occurrence and of resulting consequences requires data, tools, and methods not typically used by fire protection engineers. In addition, there are two approaches to the concept of probability (likelihood): the frequentist approach and the subjectivist approach [1, 2]. In brief, the frequentist approach comes from classical statistics, which considers probability to be a property of a process that is ideally determined from an infinite population of data. It considers probability to be a measured value and that information needed to estimate it can come mainly from observing the process. (For example, one can determine the probability of a coin landing with "heads" up or "tails" up only by flipping the coin an "infinite" number of times.) The subjectivist view, however, holds that probability has a value at any time that represents the total available knowledge about the process at that particular time. (For example, one can look at a coin having a "head" and a "tail," assess whether it is well balanced, observe a single coin toss, and estimate the probability of getting a "head" or a "tail" if one flips the coin again.) In practice, the main difference in approach is often one of how nonstatistical information is treated in the risk analysis. The frequentist approach attempts to keep the statistical values unaltered in the analysis, while commenting on limitations and bias so that they can be considered in the overall evaluation of the risk at the end of the process. The subjective approach attempts to generate numerical values using nonstatistical information and integrate them directly into the risk calculation.

Regardless of the difference in approach, the availability of information to determine probabilities is critical, as is the applicability of the probability information to the problem at hand. For example, (1) what data are available (e.g., how many fire ignitions have there been in office buildings in the past 10 years that did not result in significant fire damage?); (2) how applicable are historical data as an indicator of future events (e.g., were fire loss data from cellulosic materials prior to 1960 an appropriate indicator of fire losses involving synthetic materials after 1960?); and (3) how might changes to the building or its contents in the future impact the likelihood of fire occurrence and/or magnitude and type of consequences?

It is difficult to provide comprehensive guidance on what obstacles one should look out for when using fire safety data for fire risk analysis. However, some simple questions can be used to assess the suitability of data for fire risk analysis. Suggested key points for reviewing data include

- What is the set of cases that the data are drawn from?
- What scenarios are the data measuring?
- How similar is the building being analyzed to the cases being considered?
- Especially if the data are from another country, how do definitions, thresholds, and other design and collection rules and practices affect the relevance to the building being analyzed?

Other considerations include

- How old are the data (are they still applicable, given changes that may have occurred since the data were obtained)?
- Are corroborative data available?
- Are the data from statistical studies or based on engineering judgment?

When reviewing the results of the analysis, consideration should include

- Do the answers look realistic when compared to historical data for similar events?
- How sensitive are the results to data?

The above points to a critical factor in building fire risk analysis: there will be uncertainty, variability, and unknowns in any risk problem. How these factors are identified and addressed will be critical to the risk analysis, especially with respect to the stakeholders involved in passing judgment on the "acceptability" of the risk. Should point values be used or are distributions preferable? How is the variability in parameters such as building occupant health and ability addressed in the analysis? These are just a few items that must be addressed.

Building fire risk analysis is one of the main ways of assessing uncertainty, sensitivity, and variability in unknowns in fire protection engineering; for example, will a particular system operate in a fire, and what are the potential consequences and risk implications of system failure? Building fire risk analysis requires evaluation of the likelihood of fires occurring and the consequences that may result. Developing these evaluations requires significant information from numerous sources, including objective data (e.g., historical fire loss data), subjective judgment, and input from interested and affected stakeholders. To help the diverse stakeholders involved in building fire risk analysis better understand how each views each building fire risk problem, and to address the preceding issues, an understanding of risk characterization is needed.

Building Fire Risk Characterization

Risk characterization requires a well-defined problem that those involved agree with, a sound scientific base, the proper use of analytical techniques with proper consideration of uncertainties and unknowns, and sufficient discussion and deliberation so that everyone understands all of the issues [3]. The risk characterization process will likely require several iterations as new information and data become available and as participants gain better understanding and raise more issues. It should be an inclusive, informed, consensus-building process, and not one where one person or group dominates the deliberations and/or analysis and forces a solution.

To help characterize building fire risks, a number of questions need to be asked: [1, 3–6]

1. Who or what is exposed?
2. If it is people, what groups are exposed?
3. What is posing the risk?
4. What is the nature of the harm or loss?
5. What qualities of the hazard might affect judgments about the risk (e.g., voluntary/involuntary, known/unknown, etc.)?
6. Where is the hazard experience?
7. Where and how do hazards overlap?
8. How adequate are the databases on the risks?
9. How much scientific consensus exists about how to analyze the risks?
10. How much scientific consensus is there likely to be about risk estimates? How much consensus is there among the affected parties about the nature of the risk?
11. Are there omissions from the analysis that are important for decisions?

Various tools and methods exist to help obtain needed information for building fire risk characterization. Several of these are outlined in the following section. Detailed discussion on the above questions can be found in the literature [1, 4–6].

Methods for Gathering Building Fire Risk Information

To help obtain the necessary information regarding what is valued and how, the likely impacts of fire and fire effects, how particular fire hazard conditions may occur, and the likelihood of losses occurring, several tools, methods, and approaches are available. This section provides a brief overview of various tools, methods, and approaches available to fire protection engineers for the purpose of gathering needed information. This section does not constitute a comprehensive review, and readers are urged to consult the fire and risk literature for more tools, methods, and approaches and for more details on the approaches discussed herein.

As part of a risk analysis, one should identify what is of value, assess the hazards that may result in harm or loss to that which is valued, and make an estimate regarding the likelihood of the loss occurring. In building fire risk analysis, life safety, property protection, business continuity, the environment, and/or heritage are the value foci. To determine how they are valued and the associated levels of unacceptable impact (damage, injury, or failure), consequence analysis is used. To determine the extent of exposure from potential hazard situations, fire hazard assessments are undertaken. To complete the risk analysis, evaluation of the likelihood of hazard events occurring and their levels of impact that result in unacceptable or intolerable levels of risk is required.

Consequence Analysis

To determine how a hazard may occasion loss or harm to that which is valued, some form of consequence analysis is required. Consequence analysis, a key component of risk characterization, is concerned with determining the potential impacts of a hazard event without consideration of the likelihood of the consequences occurring. Consequence analysis is more difficult than hazard assessment, in that it may not always be clear in what ways and to what extent something is valued and how the loss should be characterized. For life safety, the line may be drawn simply between life and death, or may be extended to cover quality of life, pain and suffering, and/or rehabilitation after a fire-induced injury. For property protection, it may not always be clear to the interested and affected parties where, how, and how much damage may occur. Some may not realize that code compliance, for example, can be significantly different than protecting their building, process, contents, or other assets of value. The issues can get even more complex for assessing potential business continuity impacts and damage to historically important buildings or contents. Nonetheless, such differences are important for characterizing risks, determining tolerable impacts, and selecting acceptance (damage, failure) criteria, and are why interested and affected parties must be involved in the process.

The nature of consequence analysis will vary based on the risk problem, with the issues of what is valued and how it is valued being two central foci. Determination of what is valued and how it is valued may require facility surveys, research into the impact of fire effects on that which is valued, an understanding of the state of knowledge for assessing impacts on that which is valued, and discussions with a wide variety of interested and affected parties. Uncertainty, variability, and unknowns will be key factors in many consequence analyses, especially as related to such factors as available data, randomness in affected populations, selection of acceptance criteria, selection of methods for assessing the impacts, and values of the affected and interested parties. (See Chap. 76 for discussion on uncertainty, variability, and unknowns.)

In the taxonomy of performance-based fire safety design, consequence analysis is often described in terms of establishing fire safety goals, objectives, and criteria; and tools, methods, and approaches to determining fire safety performance can be found in pertinent references [7–10]. Although such documents contain some guidance on selecting acceptance (performance) criteria, there is often a need to refer to more specific resources for details on particular physiological thresholds, material failure points, and related impact-related criteria (e.g., see pertinent chapters in this handbook). For monetary valuation equivalents, guidance can be found elsewhere in this handbook (see Chap. 79 by Ramachandran and Hall) as well as in the general risk literature [11–13]. It is worth noting, however, that valuation in terms of monetary worth can be difficult to achieve. This is especially true for life safety, where identifying a value for human life can be difficult (if not impossible) and sometimes controversial [14–21]. Discussions on monetary valuation for the purpose of insurance/no-insurance trade-offs can also be found in the literature [22, 23].

One way of potentially addressing this controversy is to try to quantify the risk/cost effectiveness of alternative life safety solutions in terms of "cost per life saved," "cost of premature death averted," or similar approach. By using such approaches, risk/cost effectiveness can be compared without placing a value on human life. See Chap. 81 for discussion on benefit-cost analysis and related monetary valuation issues.

Hazard Assessment

The purpose of a fire hazard assessment is to identify possible sources of fire ignition and various conditions that may result from the fire without consideration of the likelihood of occurrence. Fire hazard assessments typically involve surveys of facilities or processes to obtain such information as potential ignition sources, potential fuel sources, arrangement of fuel packages, building and compartment configurations, and presence of fire safety features. Armed with this information, one either assumes ignition or established burning and estimates or predicts the fire growth, spread, and impact under a variety of fuel, compartment, and fire protection systems configurations. Identification of ignition sources requires knowledge of how ignition can occur (see Chap. 18 in this handbook) and often involves simply a visual survey. However, visual inspections may be supplemented by general or facility-specific loss data, material hazard data sheets, and other sources of information as appropriate. This latter point is important, as a review of historical loss data can help minimize the chance of focusing too closely on unique hazards, while overlooking more common, but equally important, hazards.

There are a number of tools and methods available to the fire protection engineer for the purpose of fire hazard assessment. Checklists are often used as a quick method to verify compliance with codes, standards, or recommended practices. They can be as simple or as detailed as needed, and can provide a good foundation for inexperienced persons to gain an understanding of potential hazards by making them focus on areas of concern. They can be used during design, as part of an approval process, and/or as part of an inspection and maintenance program. A potential downside is that too much focus on the checklist can lead to other hazards or potentially hazardous conditions being ignored. In addition, the user, if inexperienced, may not understand the relative importance of one item on the checklist over another, or how the hazard condition could manifest itself.

Safety reviews are typically performed for existing facilities and involve regularly scheduled visual inspections [24]. The primary purpose is to identify conditions or procedures that could lead to accidents (initiating events), illness, injury, or damage (consequences). As with a checklist, the scope of the review can be as simple or complex as deemed necessary. It may be simply a walk-through or may require review of material safety data sheets (MSDSs), testing of systems, or other safety-related functions. Checklists and a routine schedule are often helpful components of a safety review.

A "what if" analysis is primarily a conceptual divergent thinking process used to help identify areas of concern for use in checklists, safety reviews, and the following tools and methods [24]. It involves people asking "what if" about potential situations or scenarios that could arise, such as "what if the pump fails?" or "what if the operator mistakenly activates switch A instead of switch B?" "What if" analysis is typically informal and is used as a basis for initiating more detailed analyses.

Checklists and "what if" analyses can be combined as part of hazard and operability (HazOp) studies [24]. A HazOp study primarily involves taking a checklist, an MSDS, a system flow or operation chart, or other document about a process or system and systematically asking questions aimed at determining outcomes for specific actions. For example, if a valve on a drawing is labeled "flow," the question might be asked, what happens when there is "no flow"? Where the answer is unknown or unsatisfactory, additional analysis is undertaken. HazOps tend to be quite formal.

More formal approaches include failure modes and effects analysis (FMEA) and failure modes and effects and criticality analysis (FMECA) [24]. FMEA and FMECA require a tabulation of equipment, components and systems, their failure modes, the effect of the failure, and the criticality of the failure (in a FMECA). These analyses typically focus on single-mode failures and usually do not include human failure analysis.

If, after application of one of the above methods, a potential failure mode or hazard condition is deemed to require more detailed analysis, fault tree analysis (FTA) or event tree analysis (ETA) is often used [24]. FTA is essentially a "reverse thinking" or "top down" deductive technique that focuses on one particular event that could (or did) occur (typically an accident) and provides a structure for evaluating the potential causes of the event (e.g., given failure X, what could have been the cause). It does this by providing a structure, in the form of a graphic representation of a logic model, that an analyst uses to display various events, conditions, actions, and outcomes. The output of an FTA is a set of combinations of root or initiating events that could lead to (or could have lead to) a failure and may include component, equipment, system, operating and/or human actions, failures, or errors. Although FTA may be a qualitative tool as used in hazard assessment, it can be used as a quantitative risk assessment tool if probabilities or frequencies are assigned to the various initiating or root causes.

Fault tree analysis (FTA) can be used to predict the probability or frequency of an event's outcome by combining the probabilities or frequencies of initiating events using logic gates (primarily AND gates and OR gates), as illustrated in Fig. 75.1. Use of an AND gate implies that all branches leading into the upper event must happen for the event to occur. In Fig. 75.1, using a hospital as an example, "failure to detect a fire on a ward within 5 min of ignition" is expected to occur only if "failure to detect by automatic fire detection system" AND "failure by staff to observe (detect) fire" conditions are met. Use of an OR gate implies that only one of the connected branch events must occur. For example, "failure to detect by automatic fire detection system" could result if either "no automatic fire detector present" OR if "failure of automatic detector to detect fire" occurs. By assigning a probability or frequency associated with each event in the tree, and combining the probabilities or frequencies according to the AND and OR gates, the probability or frequency of the top event can be estimated [25].

Whereas FTA begins with a failure and provides a structure to look for potential causes, event tree analysis (ETA) provides a structure for postulating an initiating event and analyzing the potential outcomes. The principal tool is a decision tree (as used in decision analysis) with branches for success or failure (yes or no, or other binomial output). The basic approach is to identify an initiating event, identify systems or strategies intended to mitigate the event, and ask the "success or failure" question for each system or strategy, building the tree in the process. As with FTA, ETA is primarily a qualitative tool as used in hazard assessment but is often used as a quantitative risk assessment tool by assigning probabilities, much the way probabilities are used in a decision tree (see also Chap. 83 and other sources [26–28]).

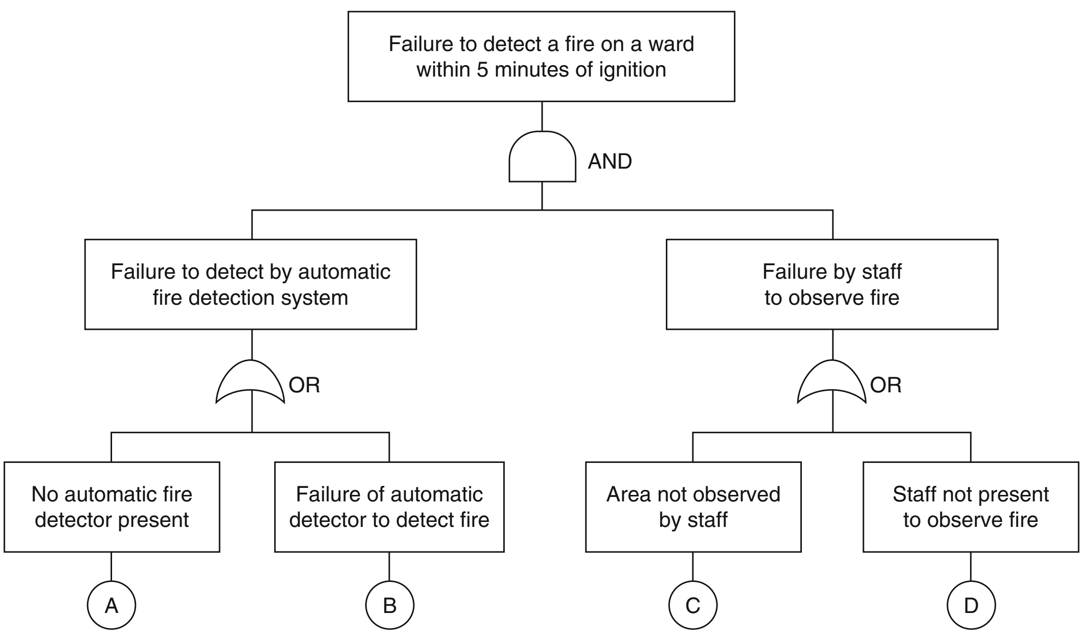


Fig. 75.1 Simple fault tree—fire detection in a hospital ward

For example, consider the simple event tree in Fig. 75.2. The initiating event is "ignition inside hospital ward" and the aim is to assess the probability or frequency of that ignition resulting in a "small fire" or a "fully developed fire" (more developed trees could include other options, such as "self-termination"). For each question (statement, or intervention), either a probability of occurrence or frequency can be assigned (e.g., the probability of fire growth is X, or fire growth has been observed to occur Y times per year for similar occupancies). If taking a probability approach, conditional probabilities for each factor can be estimated using a combination of historical data and expert judgment, as appropriate, resulting in a probability estimate for a specific outcome (scenario). By assessing the likelihood of the initial event in conjunction with the probabilities of the various factors, the frequency of the outcomes (scenarios) can likewise be estimated [25].

The data for event trees can be taken from fire statistics and other observations and measurements [29]. The effectiveness of an event tree in representing real fire events can be undertaken by quantifying the conditional probabilities for all fires in a type of building and then comparing the predicted outcome frequencies with the frequencies of deaths and injury in real events in that data set [30].

Cause-consequence analysis combines the forward thinking concept of ETA with the reverse thinking concepts of FTA to provide a more broadly encompassing picture of possible sequences of events [24]. Although primarily a qualitative tool as used in hazard assessment, it can be overlaid with frequencies or probabilities where used as a quantitative risk assessment tool.

Human error analysis describes a group of task-analysis-based qualitative techniques used to better understand the types of errors people might make and under what circumstances. Although helpful in better understanding potential sources of error, it has been noted that some such analyses treat human error and reliability in much the same way as mechanical systems, and it is argued that "desirable systems states" may be a more appropriate model [31]. In essence, "desirable systems states" focus on the goals that systems are aiming to achieve; and with why, what, and how questions, focus in on the potential for errors in various states of the system. Where people are part of the system, this approach highlights areas of concern and uncertainty related to human reliability and error.

In addition to the above methods, a variety of analytic tools, such as models, are used to assist in the hazard assessment. As Britter [32] points out, models are useful for a variety of tasks, including

- A means of summarizing extensive analytical and experimental results in order to assist in the transfer of that knowledge and to focus attention on deficiencies in the knowledge base

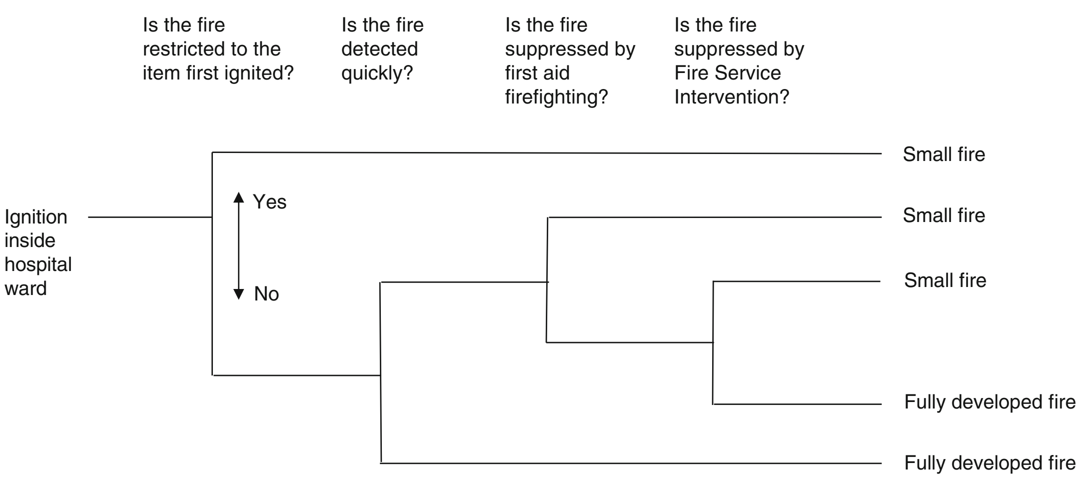


Fig. 75.2 Simple event tree—fire extinguishment in a hospital ward

- A means to provide knowledge in a form accessible to users with varying levels of expertise in the subject area
- A means to highlight the sensitivity of the output to the various input parameters
- Predictive tools for various scenarios of interest that have not, themselves, been tested

As used here, models can be mathematical or physical. Mathematical models include empirical models (based on correlation), models based on fundamental equations, analytical models (exact or approximate solutions to a set of equations in closed form), and numerical models (computational models). Physical models (simulations) rely on actual physical representations, often at a reduced scale (e.g., a wind tunnel), and sometimes with the actual material of concern (e.g., air movement in a wind tunnel), and sometimes with different materials with similar properties. Models are widely used to support fire hazard assessment. Details on fire effects modeling are provided elsewhere in this handbook and can be found throughout the fire literature. It is worth noting here that, regardless of the model one uses for fire hazard assessment or risk analysis, one must understand its uses, applications, and limitations; and appropriately account for the sources of uncertainty and variability that matter (see Chap. 76 for more details).

Causal Relationship of Initiating Events, Hazards, and Consequences

In addition to being viewed as separate components, consequence analysis and hazard assessment can be thought of as two parts of a process for identifying and evaluating the potential for unwanted consequences (loss or harm of something that is valued) given some initiating event. This definition implies that an event without unwanted consequences does not constitute a hazard and that there is a causal relationship between initiating events and unwanted consequences. One way to assess the potential for some initiating event to result in unwanted consequences is to view the situation in terms of a causal sequence, which looks at the situation as starting with some basic human need and ending in some consequence(s) [33]. The basic causal structure is illustrated in Fig. 75.3.

In brief, there are a variety of basic human needs, such as shelter, companionship, and love, which in turn lead to wants or desires. These wants or desires often result in the application of some technology to address the want. Unfortunately, the choice of technology can result in an outcome that exposes someone or something to loss or harm, resulting in some potential for unwanted consequences. To change the potential for unwanted consequences, one can modify the causal sequence by initiating one of six alternatives: modify wants, alter technology, block events, block outcomes, block the exposure, or block the consequence. This can be illustrated by example.

One basic human need is protection from the elements. To address this need, humans want shelters that provide protection from things such as rain, snow, and cold temperatures. To address this want, they may choose to live in structures that provide protection from rain and snow and can be heated to a comfortable temperature. Furthermore, they may choose to build

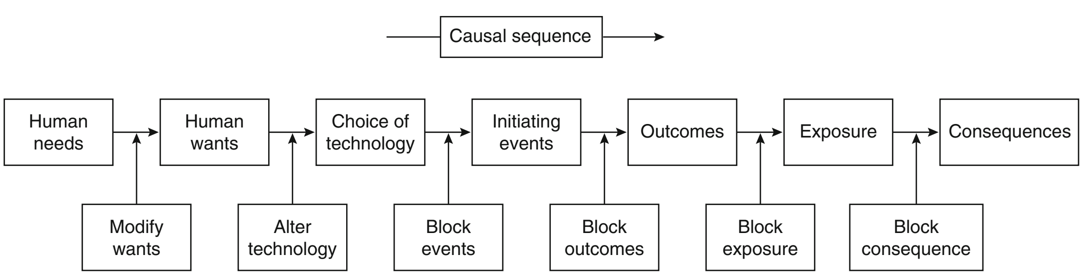


Fig. 75.3 Causal sequence [33]

these structures out of wood and to use an open fire as a source of heat. Under "normal" circumstances, everything could work fine, and the choice of technologies would provide the desired benefits. However, there could be some event, such as the blocking of a ventilation opening or too much fuel being put on the fire, that could lead to potentially unwanted outcomes. These outcomes, such as the presence of smoke, CO, or excessive temperatures in the structure, could then lead to exposures to people and property and ultimately result in unwanted consequences. Such a sequence can be illustrated diagrammatically, as shown in Fig. 75.4.

By applying an assessment methodology such as the causal sequence, one is able to visualize events, outcomes, exposures, and consequences in a systematic manner. The application can be as simple or as complex as needed, with the addition of multiple events, outcomes, exposures, and consequences and the addition of feedback loops providing further detail. Furthermore, the approach is compatible with various other hazard assessment techniques, as outlined previously, that may be more focused on specific parts of an overall assessment problem. This is illustrated in Fig. 75.5.

As can be seen in Fig. 75.5, numerous methods and approaches can be used for specific hazard assessments. Although some are applicable to a variety of problems, many are intimately associated with specific characteristics of the hazard, the type of risk problem, the current state of knowledge, and the available technology. For example, most health hazard and risk assessments (toxicological, physiological, cancer, disease) rely heavily on epidemiological studies and dose-response relationships and models [34–38]. In these cases, a causal relationship is often sought between exposure to a substance and unwanted outcomes (e.g., exposure to asbestos and the causation of cancer). Such approaches may be considered if an incapacitation assessment is being undertaken. For technology-related hazard and risk assessments, the focal point is typically the relationship between initiating events and outcomes (through to consequences). For these analyses, methods such as those outlined previously, like failure mode and effects analyses, fault tree analyses, and event tree analyses, are often used [2, 24, 39–43].

Fire Safety Concepts Tree

A useful tool for fire hazard and consequence analysis is the *fire safety concepts tree* [44]. The fire safety concepts tree is a graphical

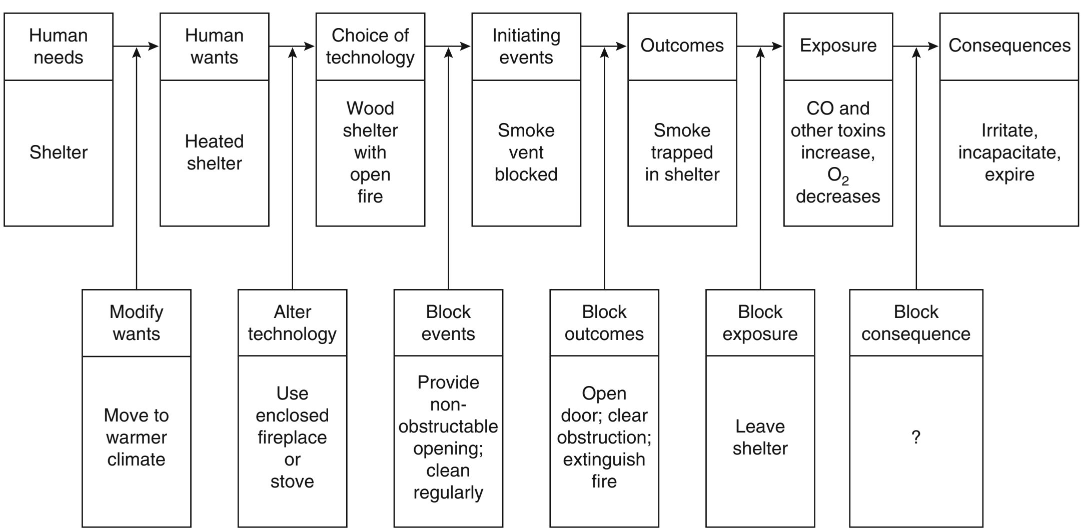


Fig. 75.4 Illustration of potential unwanted fire-related consequences

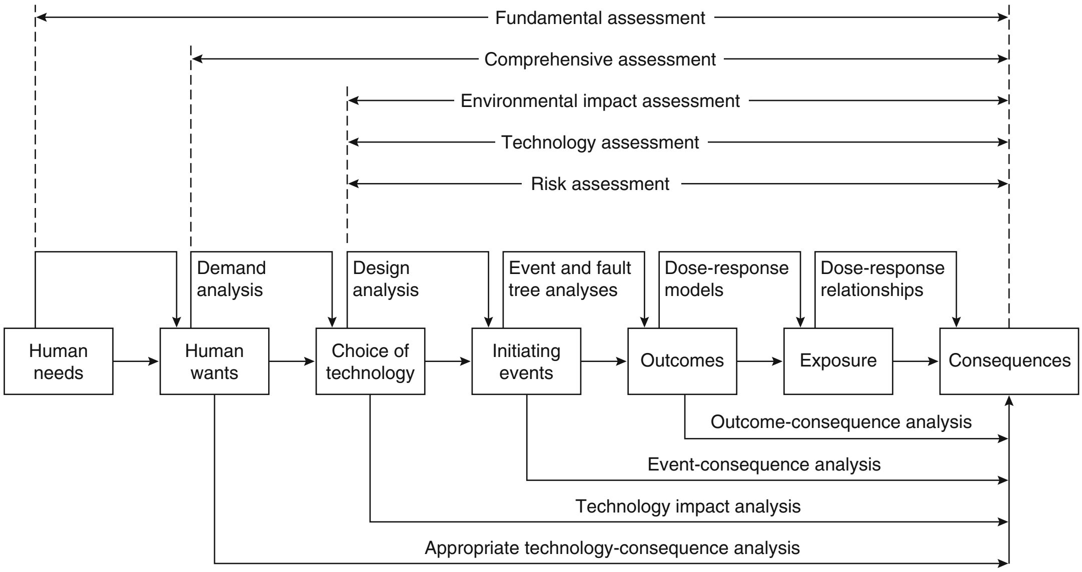
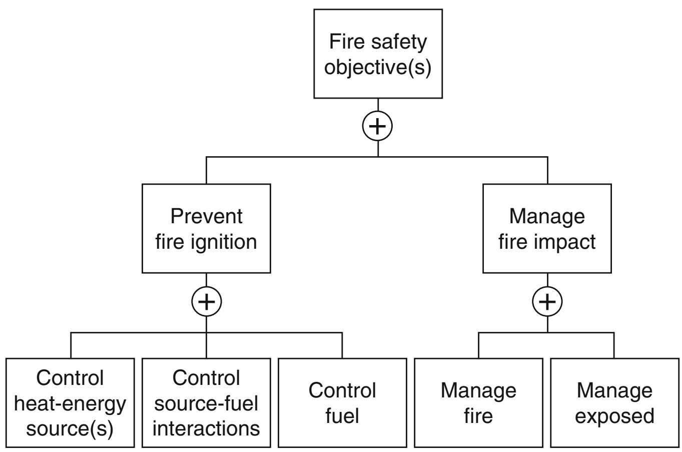


Fig. 75.5 Modes of analysis compatible with the causal structure [33]

Fig. 75.6 Top branch of the fire concepts tree [44]



representation of the deliberations and professional judgments of the NFPA Technical Committee on Systems Concepts for Fire Protection in Structures, and represents one way in which building fire safety can be viewed [45]. It is divided into two primary branches, "prevent fire ignition" and "manage fire impact," with the concept being that one or the other must be accomplished in order to meet one's fire safety objectives. One can use the tree as a guide to evaluate potential fire impacts in those cases where a building fails to meet the criteria of one or more branches (e.g., if ignition is not prevented, one can evaluate the ability of the building's systems to manage the fire impact). One can also modify the fire safety concepts tree into the form of an event tree or a decision tree for risk analysis.

A portion of the fire concepts tree is provided in Fig. 75.6, which shows the top-level choices, "prevent fire ignition" or "manage fire impact." A complete version of the event tree can be found in NFPA 550, *Guide to the Fire Safety Concepts Tree* [44].

Assessing the Likelihood of Occurrence

Thus far, the risk analysis components of determining what is valued and assessing the hazard conditions that may occasion the loss or harm have been discussed. The final component is concerned with obtaining a judgment on the likelihood of specific losses occurring to what is valued. The concepts of frequency, probability, and the differing views of probability are important to this discussion.

One dictionary defines probability as the likelihood of an occurrence expressed as the ratio of the number of actual occurrences to that of possible occurrences, and frequency as the rate of occurrence [46]. Inherent in the latter definition is the concept of events per unit time. Thus, a frequency of fire ignitions during a specific period of time, on its own, is not an indication of the probability of fire ignition. To obtain a probability of fire ignition, an estimate of the number of possible occurrences is required as well. For example, a hypothetical statistic of 20 fires per year occurring in toasters as they are switched on is a *frequency*. To estimate the *probability* of a fire in a toaster when it is switched on, one would also need data on the total number of times toasters are switched on per year. If one had data that indicated that toasters are switched on 20 million times per year, one could then estimate the probability of fires in toasters as they are switched on as 20 fires per 20 million toaster starts per year, or one in a million per year.

Probability theory is a branch of mathematics that deals with the modeling of uncertainty through measures of relative likelihood of alternative occurrences [47].

This is one place where the differing approaches of objectivism and subjectivism come into play: the estimation of the likelihood of occurrence. As noted earlier in this chapter, some approaches tend to give more weight in the analysis to data from observed events with a narrative to address the effects of current state of knowledge to inform a judgment, whereas other approaches tend to utilize the current state of knowledge coupled with judgment to modify data from observed events as part of the analysis. This distinction is important to remember when certain high-consequence fire events are relatively rare and thus data are somewhat limited. In addition, people can change the nature of the fire hazard over time (e.g., by reconfiguring buildings, changing contents); and the material composition of building products and contents will likely change, making the ability to predict future hazards or risks challenging at best.

Such conditions provide an argument for the use of subjective probability measures over objective measures for building fire risk analysis. Because data are often scarce, and actual occurrences and possible occurrences may not be precisely known, it is often necessary to make estimates. At issue is how one chooses to make the required estimates [48]. For example, whereas one may have frequency data on fire ignitions in a particular class of buildings, a subjective judgment relative to the number of possible future occurrences may be more appropriate than a judgment based on statistical treatment of limited and potentially highly uncertain data.

Regardless of the differences in philosophy between objectivism and subjectivism, data are needed. Sources of fire loss data, including fire frequency data, can be found in Chap. 78 by Hall and Ahrens, as well as in various other publications, including annual [49] and periodic [50, 51] journal articles, NFPA reports [52], government reports [53], and handbook appendices [10, 54, 55]. Likewise, approaches which illustrate how data are used in different ways for evaluating and characterizing risk can be found in the literature [56–60]. In addition, it should be clear that the concepts of uncertainty, variability, and unknowns, by the nature of the problem, are critical concerns in risk analysis and must be appropriately addressed (see the following section as well as Chap. 76).

FN Curves

In managing building fire risks, it is important to differentiate between high-frequency/low-consequence events and high-consequence/

low-frequency events. This is important because society tends to be less tolerant of high-consequence events (consequence aversion), and the means for managing risks may be affected by the nature of their frequency and consequence.

FN curves were developed in the nuclear industry in the 1960s [61] as a means of analyzing and communicating the different levels and natures of risks, particularly those with the potential for high consequences but with low frequencies.

Figure 75.7 [62] shows an FN curve for multifatality accident rates. It is possible to see that road fatalities are the highest level of risk, but are at the high-frequency/low-consequence end of the graph; whereas aircraft crashes risks are higher at the high-consequence/low-frequency end of the graph, where society tends to show greater concern.

Figure 75.8 shows how FN curves can be used to compare levels of fire risk in different parts of a building or indeed in different buildings [63].

As Low as Reasonably Practicable (ALARP)

One way of testing risks that are neither negligible nor intolerable is the principle of as low as reasonably practicable (ALARP). That is, if the cost of risk reduction or the benefits of the activity grossly outweigh the risks, then the level of risk can be said to be ALARP [64]. The degree to which a risk is ALARP is usually calculated using cost-benefit analysis.

EXAMPLE: Financial Risk Assessment Using Cost-Benefit Analysis

Concern was expressed by a major bus operator with respect to the risk to business from fires in bus garages. In particular, the operator was interested in whether or not it should install sprinkler systems in its existing bus garages or take some action. Obviously, the cost of this would be considerable, and so the bus operator commissioned

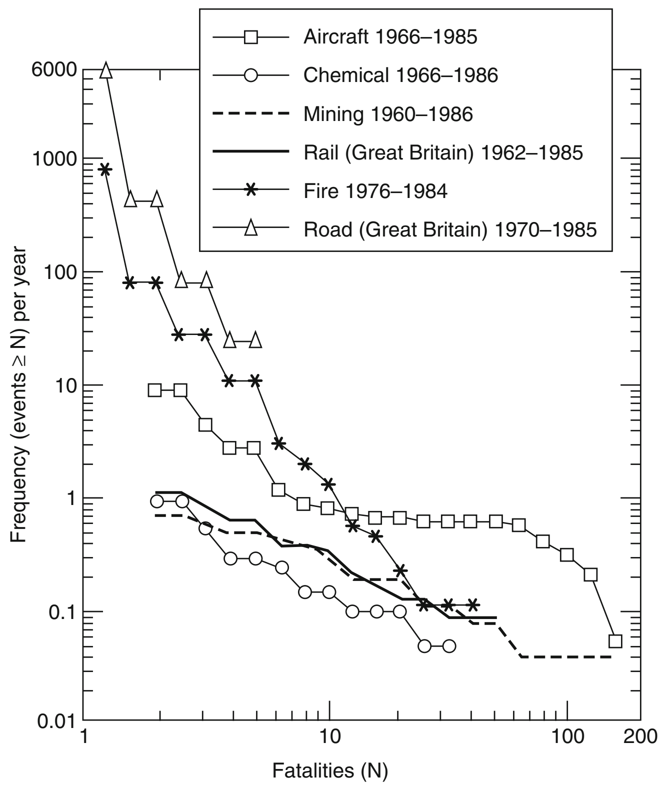


Fig. 75.7 Frequency of multiple fatality accidents in the United Kingdom [62]

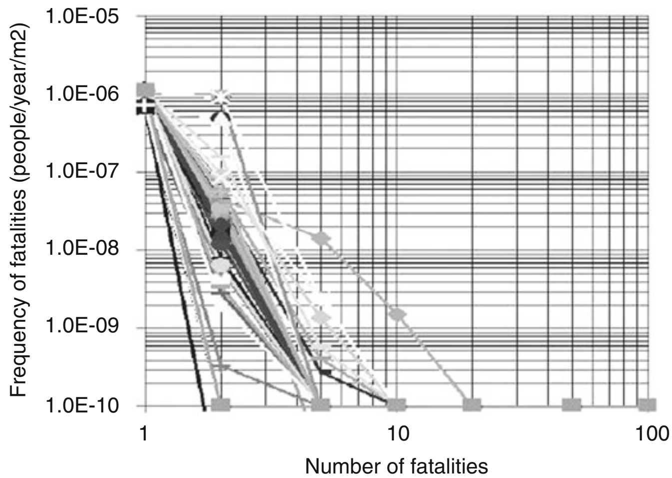


Fig. 75.8 Example of FN curves for fire risk/ occupant year in a building [63]

a study to quantify the benefits in terms of property protection [65].

This risk assessment involves

1. Identifying events that could give rise to the outcome of concern
2. Estimating how often the events happen
3. Estimating what the severity of the outcome of those events would/will be
4. Assessing the implications of the level of risk

Identifying Events

The events of concern are fires causing significant damage to vehicles and property in bus garages. From operating experience, fire safety judgment, and full-scale fire tests, these events were narrowed down to one "reasonable worst case" event:

A seat fire at three points on a double-deck bus parked among others.

The risk parameter chosen for the study was the cost of fires per calendar year. This could allow the bus operator to put these risks in context with historical data on other risks.

Estimating the Frequency of Events

To estimate how often the fire event happens, historical data were collected on how often fires occur on buses in garages. Because large fires on buses are relatively infrequent, there was insufficient information to directly estimate how often these severe events occur. Therefore, an event tree was constructed to help generate the missing information.

An event tree was constructed to predict the possible outcomes from an initial event (Fig. 75.9). For example, an initial event of "Seat fire in the lower saloon of a double-deck bus" may have outcomes of "Damage less than £200,000" and "Damage greater than £500,000." The likelihood of each outcome depends on other factors such as "Is the fire noticed at an early stage of development?" "Does the fire spread to neighboring buses?" or "Is the fire extinguished using fire extinguishers?"

The conditional probability of each of these other factors is estimated using historical data and informed judgment. Therefore, using the likelihood of an initial event and the probabilities of the other factors, an estimate can be made of how often an event occurs.

Estimating the Severity of the Outcome

There are several ways to estimate the severity of the outcome: using historical information, using simple analytical methods, using computer models, and/or using full-scale tests. Each approach has its advantages and disadvantages. Historical data describe what the outcomes have been in the past but may not be complete or relevant. Simple analytical methods can predict

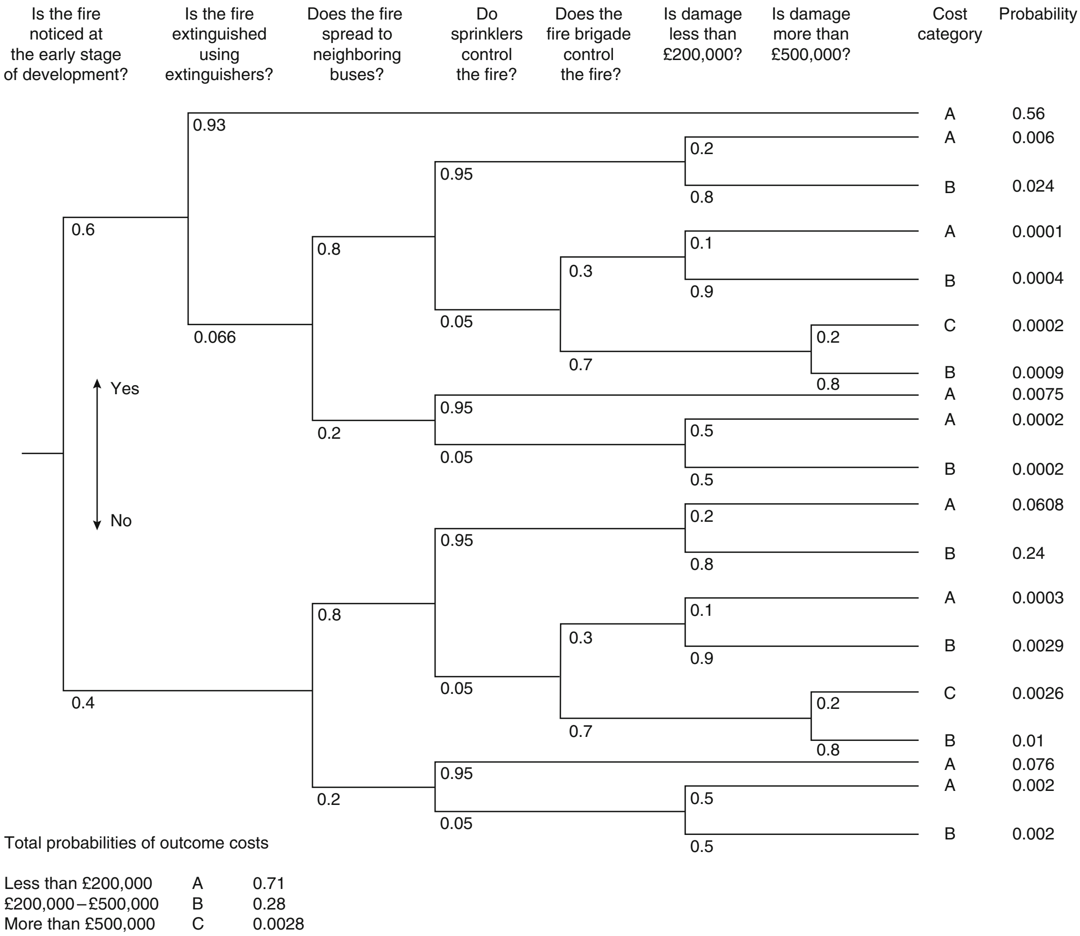


Fig. 75.9 Simplified event tree for bus garage fires with sprinklers installed [65]

the severity of outcomes cost effectively, but the answer is only as good as the assumptions made. Computer models can predict the severity of outcomes more closely but can be expensive and time consuming. Full-scale testing probably gives the most accurate assessment of the severity of outcomes, but it is usually even more costly and time consuming.

In this case the severity of the outcome (i.e., losses due to damaged buses/garage) depended heavily on the spread of fire from bus to bus and the effective spray density of different sprinkler systems. Therefore, a combination of full-scale testing and computer modeling was used to predict fire growth, fire spread, and the effectiveness of sprinklers.

Results

The risk assessment indicated that, for the event identified, a higher than ordinary level of sprinkler spray density was necessary to prevent fire spread from bus to bus. The frequencies of fires in bus garages was about 0.1 per garage year. The fire risk was then calculated for the bus garages with and without sprinklers. The difference between the two figures is the benefit rate from reduced property losses by fitting sprinkler systems, and this was of the order of £2000 per year (but this varied with the size of garage).

Historical accident data indicate that the predicted risk of damage is pessimistic; very few records of such fire damage could be found. Having quantified the benefits of sprinklers in reducing risks in bus garages, cost-benefit analysis was used to assess whether they would represent a good investment in fire safety.

Cost-Benefit Analysis

The first step was to determine the total costs of the sprinkler installation. This not only included the initial installation costs but also covered the annual running costs. The following list, although not meant to be exhaustive, covers the main costs included in this case:

- Design fees
- Installation/construction
- Commissioning/training of staff
- Maintenance/running and so forth

The capital cost for the sprinkler system was £25,000 with an annual maintenance cost of £100. The benefits of the new installation are then listed, including

- Reduced property loss
- Reduced consequential losses
- Reduced insurance premiums
- Improved life safety and so forth

The benefit rates from the quantified fire risk assessment were added to the difference in insurance premiums to give the total benefit rate of £2500 per garage year.

This is the figure used in the investment appraisal. Table 75.1 shows the discounted cash flow over a 30 year period. The discount factor used is 10 %; this is the norm for commercial premises and is spread over a 30 year life span (because of the life of the sprinkler system). The financial data in Table 75.1 do not represent those of any particular garage or operator but may be typical of some circumstances.

The cost-benefit analysis showed a small positive net present value at the end of 30 years. The positive figure indicated that, strictly speaking, the installation of bus garage sprinkler systems did not represent a good investment. However, the smallness of the value indicated that this was a marginal case. In the light of the risk assessment, the bus operator decided that it had sufficient redundancy and diversity of bus supply through ownership (in several garages), leasing and buying, and insurance not to require bus garage sprinklers. However, the risk assessment had highlighted several other risk management issues, such as fire safety management and the separation of the information technology (IT) center, where risk reduction was much more cost effective.

Study Conclusions

A study to assess the benefits of installing sprinkler systems in bus garages [65] indicated that there were business continuity and property protection benefits to the operator. However, the cost-benefit analysis and the operator's contingency plans meant that there was no cost-benefit or consequence case for installing sprinklers in bus garages. As a result of the risk assessment,

Table 75.1 Discounted cash flow for Bus garage sprinkler system [60]

Year	Capital cost (£)	Annual cost (£/year)	Total cost (£/year)	Savings (£/year)	Net costs/ savings (£/year)	Discount factor (9 %)	NPV of costs/ savings (£)	Cumulative NPV
0	25,000	–	25,000	0	25,000	1	25,000	25,000
1		100	100	–2,500	–2,400	0.9091	–2,182	22,818
2		100	100	–2,500	–2,400	0.8265	–1,983	20,835
3		100	100	–2,500	–2,400	0.7513	–1,803	19,032
4		100	100	–2,500	–2,400	0.6830	–1,639	17,392
5		100	100	–2,500	–2,400	0.6209	–1,490	15,902
26		100	100	–2,500	–2,400	0.0839	–201	3,014
27		100	100	–2,500	–2,400	0.0763	–183	2,831
28		100	100	–2,500	–2,400	0.0693	–166	2,664
29		100	100	–2,500	–2,400	0.0630	–151	2,513
30		100	100	–2,500	–2,400	0.0573	–138	2,375
		Total	28,000	–75,000	–47,000	–	2,375	–

the operator did implement other safeguards and fire precaution measures.

Uncertainty, Variability, and Unknowns

The extent of literature on the topics of uncertainty, variability, and unknowns indicates that identifying, understanding, and addressing these are clearly critical issues. For example, these issues pervade discussions of acceptable risk [66–69], risk characterization [3], risk assessment [42, 70–74], and decision analysis [11, 13, 75–78]. However, as one can see from a review of the various reference sources, there seems to be little consensus regarding how to treat these factors. There are several reasons for this, many of which impact building fire risk analysis and even drive the need for risk analysis, including

- The risk problem may not be clearly understood or sufficiently well defined [3, 68]. Any uncertainty in the problem definition will be propagated throughout the risk assessment and management process. If this uncertainty is large (i.e., if the stakeholders do not agree on key issues or parameters of the problem), the uncertainty in any proposed solution will be some factor greater.
- There are many types of uncertainties that go unrecognized or ignored [3, 68, 71, 73]. These include uncertainties in variables that are built into analytical tools and methods; uncertainties associated with criteria selected for assessing acceptability; and uncertainties in human behavior, attitudes, and values.
- There may be variability that is treated as uncertainty [36, 73, 74]. If the risk problem relates to the human population, for example, it should be recognized that both uncertainty and variability exist, and that they need to be addressed differently. It may not be known how many people may be exposed (uncertainty), and for any population postulated to be exposed, there will be differences among the individuals (variability). Uncertainty and variability become important when discussing issues such as using the entire population or some subset of sensitive or vulnerable persons, and if the latter is selected, what defines the subset.
- There may be unknowns that are treated as uncertainties [3, 79–81]. In some cases, it is impossible to accurately predict some event that may happen far into the future, or to control the circumstances on which certain assumptions are based. If these indeterminate events are treated as events that can be accurately predicted, the uncertainties in any solution could be significant (see Stern and Fineburg [3]).
- There may be disagreement regarding how to address uncertainties of different types. First, the differences between uncertainty, variability, and indeterminacy need to be identified [74]. Then one needs to identify appropriate mechanisms to address the uncertainty, variability, or indeterminacy. For example, Morgan and Henrion [71] argue that the only type of quantities whose uncertainty may be appropriately represented in probabilistic terms are empirical quantities. However, there are other types of quantities, such as model domain parameters, decision variables, and value parameters. For these, parametric or switchover analysis (or other) may be needed.
- There may be disagreement on a quantitative methodology (or set of quantitative methodologies) for treating uncertainty. Even if it is decided to perform a probabilistic analysis on an empirical quantity, there may be disagreement as to an appropriate approach to apply. For example, probabilistic approaches range from classical, statistical-based analyses to subjective, Bayesian analyses, with other types of quantitative or qualitative analyses scattered in between [3, 48, 82, 83]. To complicate the issue, frequentists often reject the Bayesian approach, and vice versa.
- There is concern that the data, mathematical rigor, and expertise needed to conduct a quantitative uncertainty analysis would render such an analysis impracticable in many situations, and as a result, the analysis would

not be undertaken or would be performed incorrectly [84].

To help people better understand the complex issues surrounding uncertainty, variability, and unknowns (hereafter lumped as uncertainty for convenience), various taxonomies and treatments have been suggested [3, 7, 68, 72, 85, 86]. Regardless of specific differences, much of the literature identifies the following areas as requiring consideration: scientific uncertainty; human factors uncertainty; uncertainty in risk perceptions, attitudes, and values; and decision-making uncertainty.

Scientific uncertainties result from lack of knowledge (either obtainable through further study or due to random chance and variations) and from necessary approximations. They are often among the most readily recognizable and quantifiable uncertainties and can be grouped into five subcategories: theory and model uncertainties, data and input uncertainties, calculation limitations, level of detail of the model, and representativeness [7, 32, 85, 86].

Theory and model uncertainties may arise when physical processes are not modeled due to a lack of knowledge about them or about how to include them, when processes are modeled based on empirically derived correlation, and/or when simplifying assumptions are made. Data and input uncertainties arise from inaccuracies in data collection and reporting, incomplete knowledge of specific input values and variations in those values as a function of confounding factors, and input errors made by the modeler. Calculation limitations encompass such factors as the control volume selected for modeling, the level of detail of the model, and the model-domain parameters specified. Representativeness relates to how well the modeled situation reflects reality.

In considering human factors, uncertainty and variability are present in several modes. There is uncertainty regarding who might be affected and how. That is, it is not always known who will be impacted (uncertainty or indeterminacy), and within the population affected, there will be physiological uncertainties and variability. There are also uncertainties and unknowns related to how people will react in different situations, especially under stress.

As discussed earlier, there can be significant differences in the ways people perceive and value risk, as well as in their attitudes about risk. Differing perceptions give rise to both variability and uncertainty, and capturing these differences is important. There will be situations in which age, family, infirmity, or other factors or conditions will impact perceptions of risk. There may be social, economic, philosophical, religious, or cultural differences in people's values systems. In addition, some people are risk tolerant, whereas others are risk averse. It is important to recognize these differences exist, and thus reduce uncertainty and unknowns, and better understand and address variability where it exists. Also important are the perceptions and issues of equity, efficacy, and fairness—issues of importance in risk characterization and management [78]. Here again, social, economic, or cultural differences of the interested and affected parties may play a major role.

There is also uncertainty in the decision-making process, including uncertainty about how to best define the decision problem, difficulties in assessing the facts of the matter, difficulties in assessing relevant values, uncertainties about the human element in the decision-making process, and difficulties in assessing the quality of the decisions that are produced [68].

All of these factors should be considered and appropriately accounted for when undertaking a building fire risk analysis. For more details on uncertainty and its treatment, see Chap. 76.

Building Fire Risk Analysis Approaches, Methods, and Models

This section provides a brief overview of various qualitative and quantitative risk analysis approaches, tools, and methods available to fire protection engineers. This section does not constitute a comprehensive review, and readers are urged to consult the fire and risk literature for more approaches to risk analysis and for more details on the approaches discussed herein.

Magnusson [27] suggests that there are two primary approaches to risk analysis: the single scenario, analytic safety index ß approach, and the multiscenario, event tree approach. In the single scenario, analytic safety index ß approach, there is a single-limit state described by an analytical expression developed from physically derived correlation (e.g., mass flow in plumes, smoke-filling times, radiation from flames) or from response surface equations describing output from a computer program. The design problem is formulated in terms of the limit state function, G, as $G(X_1, X_2, \ldots, X_n) = 0$. The parameters X_i are stochastic parameters describing the system, such as fire growth rate and response time of occupants. The goal is to find a solution given the constraint that $P(G < 0) < P_{\text{target}}$.

Challenges and limitations to the use of this approach include difficulty in developing appropriate analytical expressions, difficulty in developing uncertainty factors, and the limitation of being a single scenario application. Nonetheless, this approach is useful for some applications, and details can be found in the literature [26–28]. Although not developed, it has been suggested that this basic approach can be applied more broadly to the building fire problem as well [87, 88].

A response surface approach to probabilistic assessment of risk to life from fire as presented by Albrecht [89, 90] is similar to the probabilistic scenario and event tree risk assessment methodology outlined by Magnusson et al. [27] in which the probability (P), and a safety index (β), respectively, of a limit state violation is calculated as

$$P\left(\Omega_f\right) = \Phi(-\beta),$$

where Ω_f is the failure domain of the limit state function, for example

$$\Omega_f = \mathrm{G(X)} \leq 0,$$

and $\Phi(\cdot)$ is the function of the standardized normal distribution.

Since probabilistic calculations usually require a high number of evaluations of the underlying limit state it is usually not feasible to use numerically expensive models. Hence, so far only plume formulations or zone models have been utilized within those uncertainty calculations [27, 86, 91]. Yet, for performance-based life safety risk analysis it is nowadays inevitable to use state-of-the-art simulation models, such as computational fluid dynamics (CFD) or microscopic evacuation models for each scenario within a system of various possible scenarios.

In order to bypass the high numerical cost and to allow for probabilistic calculations using advanced and complex numerical models, an adaptive response surface algorithm was developed that uses so-called moving least squares (MLS) [92] with an interpolating weighting function [93] instead of the traditional global linear or quadratic regression functions [94]. These response surface formulations provide a good surrogate model with a comparably low number of required evaluations of the numerically expensive models and thus allow for a fast and accurate overall computation. The calculation of the failure probabilities is performed by exploiting the surrogate with an optimized adaptive importance sampling Monte Carlo algorithm (AIS) [95] which additionally allows to compute sensitivities to identify the highest contributors to the overall variance, i.e. the most relevant input parameters. The complete algorithm flowchart is shown in Fig. 75.10 and is described in detail in reference 89, Chap. 6.

The derived failure probabilities were then be compiled into event trees [26–28, 94, 96, 97] to perform a holistic system failure analysis. The advantage of the event tree analysis can be the identification of the most influential scenario by looking at the highest product of each scenario probability and the expected outcome if the scenario occurs. This constitutes the classic approach to quantitative risk analysis [94, 96, 97].

Another area of application of event tree analysis is the possibility to quantify the effect of fire protection systems on the safety level considering their potential failure. This can be achieved by comparing the two scenarios with and without the chosen fire protection system being functional while incorporating its probability of malfunction. Values for these failure probabilities can be found, for example, in the British

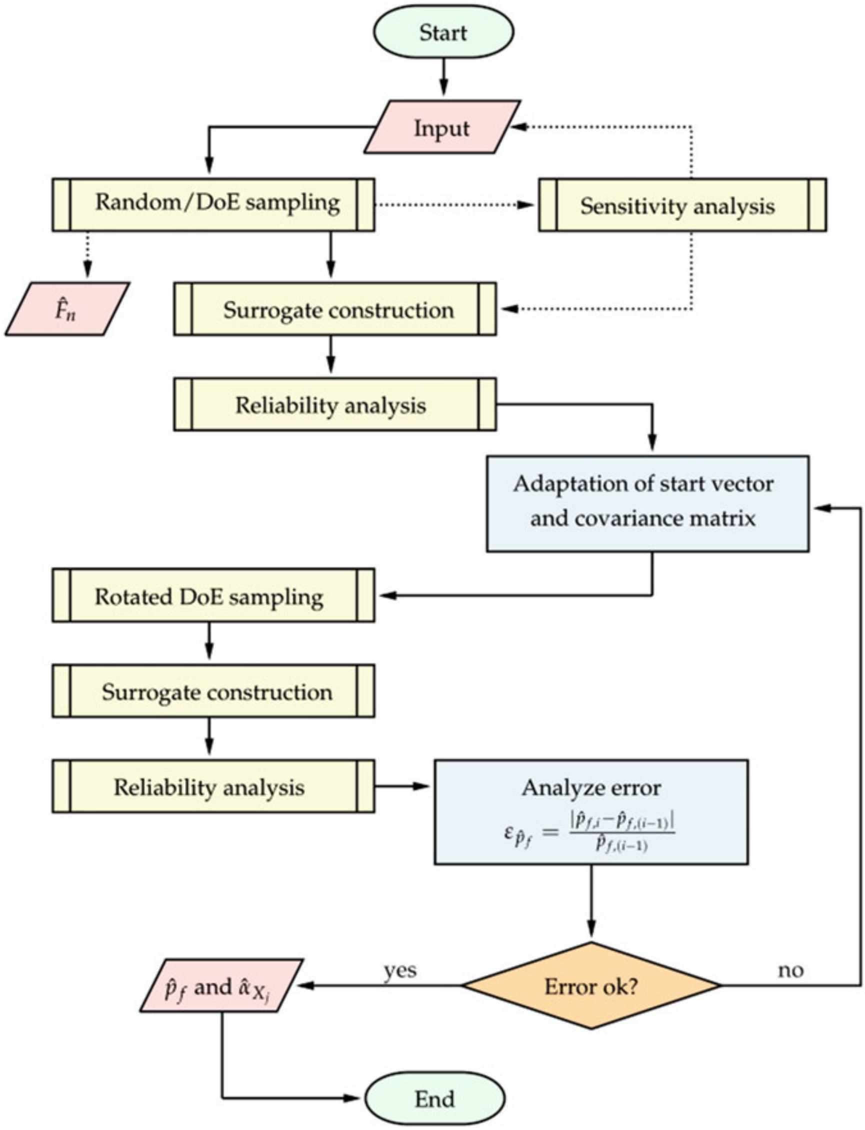
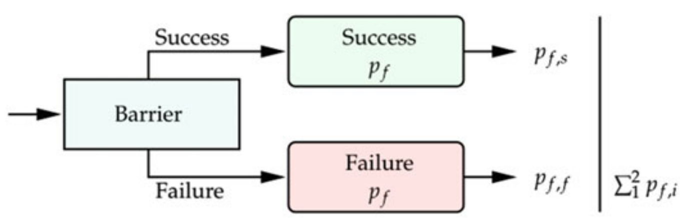


Fig. 75.10 Flowchart of the IMLS response surface Algorithm [89]

Fig. 75.11 Modeling of fire protection barriers within an event tree considering their possible failure to assess the overall impact on the safety level [89]



Standard 7974 [98]. The sub-event tree for this analysis is shown in Fig. 75.11. Further branches can be added to analyze, for example, interaction effects between various fire protection systems, such as sprinklers and ventilation systems. A comprehensive application with various scenarios and different fire protection systems can be found in reference 89, Chap. 7.

The combination of full probabilistic, performance-based scenario analysis and system analysis with state-of-the-art numerical simulation tools in fire protection engineering yields valuable quantitative information which can be used to identify the most critical scenarios and to quantify the effect of fire protection systems and thus provide a risk-optimized as well as cost-benefit optimized solutions.

To simplify this rather mathematical approach for practical application, it is possible to derive semi-probabilistic safety concepts as has been proposed [99] for the Eurocode structural fire protection where safety factors for one or multiple input parameters are derived that implicitly fulfill the required target reliability when applied. In order to develop such a safety concept for life safety analysis, for example a semi-probabilistic safety factor γ for ASET ≥ γ(RSET), those target reliabilities would have to be agreed upon first.

Event tree analysis (ETA) is often used to analyze complex situations with several possible scenarios, where several fire or life safety systems are in place or are being considered. In brief, event trees are developed for a scenario, and probabilities and frequencies for components are applied (see previous discussion on ETA). In the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* [10], the method for quantifying fire risk from multiple fire scenarios is given as

$$\sum \mathrm{Risk}_i = \sum (\mathrm{Loss}_i \cdot F_i)$$

where

Risk_i = Risk associated with scenario i

Loss_i = Loss associated with scenario i

F_i = Frequency of scenario i occurring

This relationship is similar to the earlier general discussion on engineering risk analysis; but in this case, the term *loss* is used instead of *consequence*, and the summation indicates "total" risk from multiple scenarios. This type of risk analysis, commonly referred to as probabilistic risk assessment (PRA), is widely used in the chemical process industry (see Chap. 83) and for fire safety assessments of nuclear facilities [41], and is beginning to see broader application in fire protection engineering applications [10, 26–28, 43].

Although ETA-based risk analyses methods are applicable to multiscenario situations, it does not mean such approaches are necessarily simple. This can be illustrated using a three-room example. Figure 75.12 shows an event tree for a three-room building that is compartmented as shown. For this example, the fire scenario frequency, F_i, is assumed to be uniformly distributed across the three rooms, and the consequence of a single room loss is $C/3$ (i.e., the consequence of losing all three rooms to a fire would be C) [10].

If the probability that the fire will be contained in one room is P_c, and that it is prevented from propagating to the third is P_f, then the overall risk as shown in Fig. 75.10 can be estimated as

$$\begin{aligned}R = {} & \frac{C}{3}(F_iP_1P_c) + \frac{2C}{3}\left[F_iP_1(1-P_c)P_f\right] \\ & + C\left[F_iP_1(1-P_c)(1-P_f)\right] + \frac{C}{3}(F_iP_2P_c) \\ & + \frac{2C}{3}\left[F_iP_2(1-P_c)P_f\right] + C\left[F_iP_2(1-P_c)(1-P_f)\right] \\ & + \frac{C}{3}(F_iP_3P_c) + \frac{2C}{3}\left[F_iP_3(1-P_c)P_f\right] \\ & + C\left[F_iP_3(1-P_c)(1-P_f)\right]\end{aligned}$$

where P_1, P_2, and P_3 are the probabilities that a fire will start in room 1, 2, or 3, respectively.

With some mathematical manipulation, the above equation simplifies to the following:

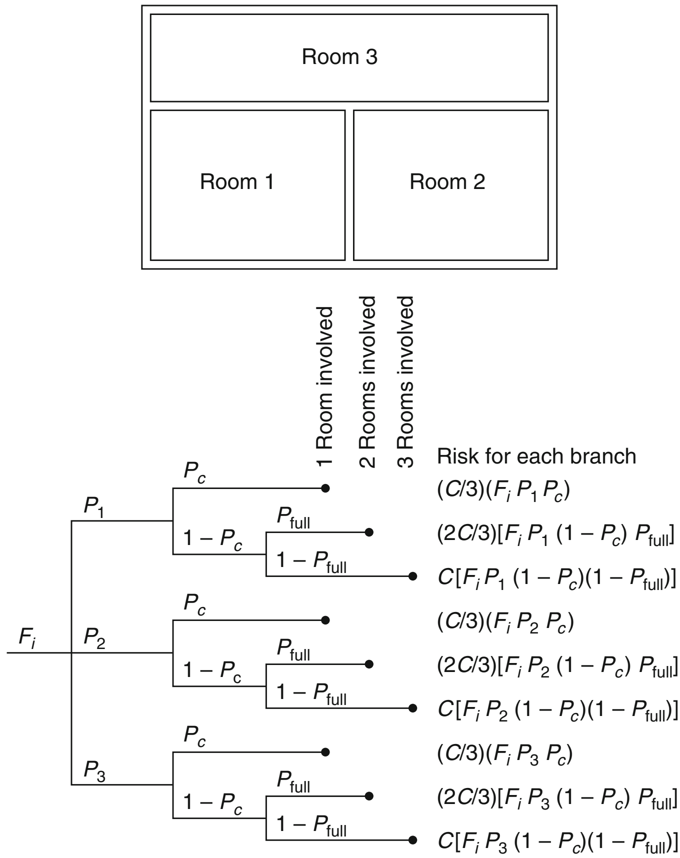
$$R = \frac{CF_i}{3}\left(3 - 2P_c - P_f + P_cP_f\right)$$

For this example, P_c and P_f can be interpreted as the success probabilities of the fire barriers. To place these results in context, numeric values will be added. If P_c and P_f are both equal to 0.1 (i.e., fire propagates 9 in 10 times), then the *risk* is

$$R = \frac{CF_i}{3}[3 - 2(0.1) - (0.1) + (0.1)(0.1)] = 0.90CF_i$$

If P_c and P_f are both equal to 0.9 (i.e., fire propagates 1 in 10 times), then the *risk* is

Fig. 75.12 Event tree for three-room fire risk analysis [10]



$$R = \frac{CF_i}{3}[3 - 2(0.9) - (0.9) + (0.9)(0.9)]$$
$$= 0.37CF_i$$

If P_c and P_f are set to unity (i.e., fire barriers never fail), then the *risk* is

$$R = \frac{CF_i}{3}[3 - 2(1) - (1) + (1)(1)] = \frac{CF_i}{3}$$
$$\simeq 0.33CF_i$$

Although this example is very simplified, it suggests how complicated a classical ETA-based engineering risk analysis can be. For each fire protection feature considered, the number of branches (i.e., potential outcomes) in the event tree will increase. Given that this increase is usually geometric, the analysis can become quite complex.

The above example also illustrates an important concept in risk-based calculations. The bounding risk for this problem would be CF_i (i.e., complete facility loss). This is the risk if all fire protection features are assumed to always fail. The risk when the fire protection features are always assumed to work (i.e., the fire barriers never fail, thus P_c and P_f are set to unity) is the lower bound risk. Thus, the potential range for the calculated risk is bounded between $0.33CF_i$ and CF_i. The better the protection, the closer the risk will approach $0.33CF_i$.

The above example can also be used to illustrate the difference between fire scenarios (all possible scenarios that could occur) and design fire scenarios (that subset of fire scenarios selected for design purposes) [10]. For example, the total range of fire scenarios for the above example could consider various room-to-room sequences (e.g., starts in room 1, then goes to room 2 and finally to room 3). If this is done, one finds that there are a total of 15 possible paths of fire propagation:

1. Starts in room 1 and is contained in room 1
2. Starts in room 1 and propagates to room 2, but not to room 3
3. Starts in room 1 and propagates to room 3, but not to room 2
4. Starts in room 1 and propagates to room 2 and then to room 3
5. Starts in room 1 and propagates to room 3 and then to room 2
6. Starts in room 2 and is contained in room 2
7. Starts in room 2 and propagates to room 1, but not to room 3
8. Starts in room 2 and propagates to room 3, but not to room 1
9. Starts in room 2 and propagates to room 1 and then to room 3
10. Starts in room 2 and propagates to room 3 and then to room 1
11. Starts in room 3 and is contained in room 3
12. Starts in room 3 and propagates to room 1, but not to room 2
13. Starts in room 3 and propagates to room 2, but not to room 1
14. Starts in room 3 and propagates to room 1 and then to room 2
15. Starts in room 3 and propagates to room 2 and then to room 1

If simultaneous propagation to the second and third rooms were considered a significant threat, there would be three additional scenarios. This brings the total scenarios to 18 before considering details such as doors being open or closed, whether people of various characteristics are in the rooms, and whether they are sleeping.

It is also important to address the fact that fire protection systems may not always be operational. As such, the concepts of availability and reliability should be addressed. A system is considered available when it is ready and able to perform its intended function (e.g., a smoke detection system is installed and working). If a system is taken out of service, even temporarily (e.g., it is undergoing maintenance), it is unavailable. A risk-based approach should consider some probability that a system will be unavailable if it is a possibility. A system that is available but not functional is considered unreliable (e.g., the smoke detection system is installed but the smoke detector opening is blocked with duct tape). Probabilities can be developed for evaluation of system availability and reliability. Availability and reliability are reported or derived as a composite value. (When the latter is the case, it should be made explicit.)

Risk-Cost Assessment Model

Because of the complexity of ETA-based risk analysis, computers are often used to enable multiple scenarios to be evaluated in relatively short time frames. Two such models, FIRE-RISK (formerly known as CESARE-Risk) and FiRECAM, are based on a fire risk and cost assessment model developed by Beck [100–102] and expanded collaboratively by Beck and Yung [102, 103].

A brief description of the current risk-cost assessment model and its submodels is given in this section [104]. More detailed descriptions are given for the design fire submodel, the fire growth submodel, and the smoke movement submodel. As for the other submodels, more details can be found in other publications [101, 103, 105–107].

The risk-cost assessment model employs an event-based modeling approach in which events are characterized by discrete times and probability of occurrence. The event-based approach is used to define the outcomes of fire growth and spread scenarios in terms of the times of occurrence of untenable conditions. The consequence of these outcomes is in terms of the number of people exposed to untenable conditions.

The risk-cost assessment model for office and apartment buildings assesses the fire safety performance of a fire protection design in terms of two decision-making parameters: (1) the expected risk to life (ERL) and (2) the fire-cost expectation (FCE). The ERL is the expected number of deaths over the lifetime of the building divided by the total population of the building and the design life of the building. The FCE is the total fire cost, which includes the capital cost for the passive and active fire protection systems, the maintenance cost for the active fire protection systems, and the expected losses resulting from fires in the building. The ERL is a quantitative measure of the risk to life from all probable fires in the building, whereas the FCE quantifies the fire cost associated with the particular fire safety system design.

To calculate the ERL and FCE values, the risk-cost assessment model considers the dynamic interaction between fire growth, fire spread, smoke movement, human behavior, and the response of fire brigades. These calculations are performed by a number of submodels interacting with each other, as shown in the flowchart in Fig. 75.13. In Fig. 75.13, the term *submodel* has been abbreviated as *model*.

The FIRE-RISK model, like FiRECAM and other more complex risk-cost models, is at present suited only to fire research or for use in assessment of building code requirements by researchers. These models are not currently well suited to use by fire protection engineers for individual building design, although that could be the ultimate aim.

FIRE-RISK has been used to assess building code requirements in Australia for Class 2 apartment buildings [108]. In particular, the current prescriptive requirements in the Building Code of Australia (BCA) have been evaluated in terms of the risks to life safety due to fire using this risk-cost model. Fatality rates per 1000 fires have been estimated for occupants in the apartment of fire origin (AFO) and in the apartments of nonfire origin (ANFO). Results of this research are shown in Table 75.2.

The lower rates for high-rise apartment buildings are likely to reflect the more stringent fire protection provisions required for buildings over 25 m under the BCA. It is suggested by Thomas et al. [108] that these results reflect the fatality rates from fire statistics for this class

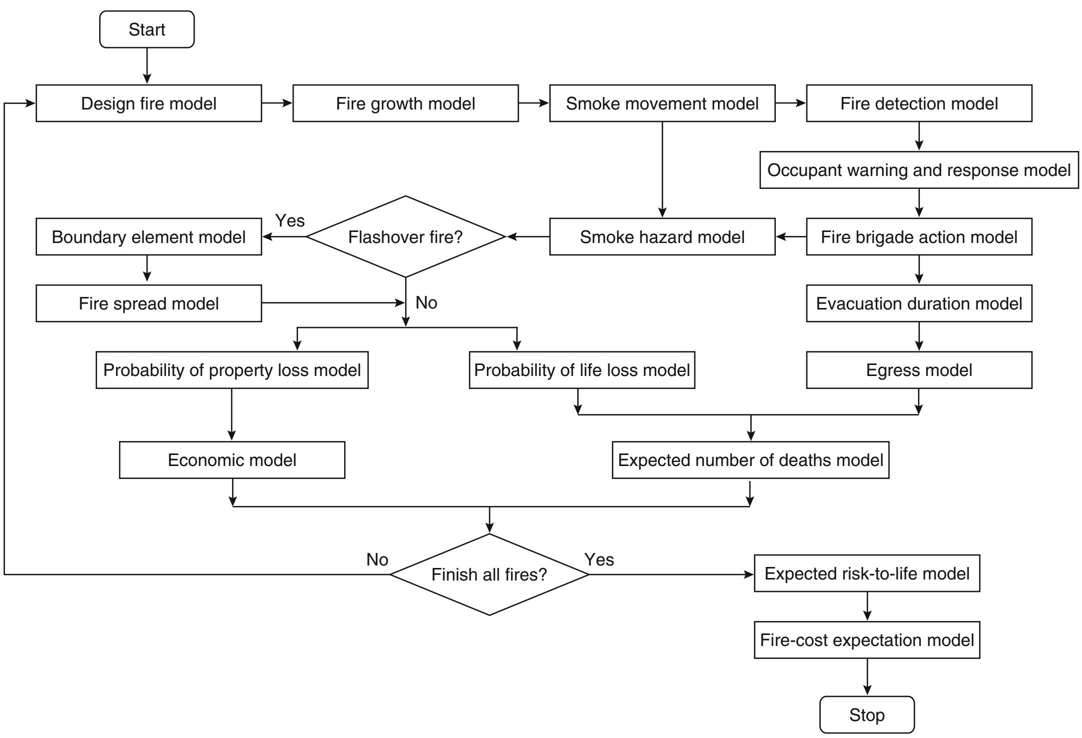


Fig. 75.13 Risk-cost assessment model

Table 75.2 Average ANFO fatality rates using CESARE-risk [92]

Building height	Fatality rate	
Low rise (<4 stories)	<0.2	ANFO fatalities/1000 fires
Medium rise (<25 m, >4 stories)	3.3–3.4	ANFO fatalities/1000 fires
High rise (>25 m)	1.7–2.1	ANFO fatalities/1000 fires

of buildings, which lends credibility to this approach.

The next step in the Australian process is to evaluate alternative fire safety solutions from those currently prescribed as deemed-to-satisfy solutions within the BCA. This would allow other prescriptive solutions to be developed and included in the BCA, which could provide building owners and designers with more flexibility to choose from a wider set of agreed prescriptive design solutions.

The risk-cost assessment model uses six design fires in the room of fire origin, and the subsequent fire and smoke spread, to evaluate life risks and protection costs in office and apartment buildings. The six design fires, representing the wide spectrum of possible fire types, are

1. Smoldering fire with room entrance door open
2. Smoldering fire with room entrance door closed
3. Flaming nonflashover fire with room entrance door open
4. Flaming nonflashover fire with room entrance door closed
5. Flashover fire with room entrance door open
6. Flashover fire with room entrance door closed

The probability of occurrence of each design fire, given that a fire has occurred, is based on statistical data. For example, in Canada, statistics show that 18 % of all apartment fires reach flashover and become fully developed fires, 63 % are flaming fires that do not reach flashover, and the remaining 19 % are smoldering fires that do not reach the flaming stage [109]. If sprinklers are installed, the model assumes that some of the flashover and nonflashover fires, depending on the reliability and effectiveness of the sprinkler system, are rendered nonlethal.

The risk-cost assessment model evaluates the effects of various fire scenarios that may occur in the building during its life. For example, in an apartment building, one fire scenario is the fire and smoke spread resulting from one design fire in any one of the apartment units in the building and during a time when the occupants are either awake or asleep. The number of fire scenarios, therefore, is the product of the number of design fires, the number of apartment units, and whether the occupants are awake or asleep.

The fire growth submodel [110] predicts the development of the six design fires in the room of fire origin. The submodel calculates the burning rate, the room temperature, and the production and concentration of toxic gases as a function of time. With these calculations, the model determines the time of occurrence of five important events: (1) time of fire cue, (2) time of smoke detector activation, (3) time of sprinkler activation, (4) time of flashover, and (5) time of fire burnout. The first three detection times are used by the evacuation duration submodel to estimate the time available for evacuation; the flashover time is used by the fire brigade action submodel, in combination with the arrival time of the fire brigade, to evaluate the effectiveness of fire fighting; and the burnout time is used by the smoke hazard submodel as part of the calculation for the maximum smoke hazard. The submodel also predicts the mass flow rate, the temperature, and the concentrations of CO and CO_2 in the hot gases leaving the fire room. This latter information is used by the smoke movement submodel to calculate the spread of smoke to different parts of the building as a function of time.

The smoke movement submodel [111] calculates the spread of smoke and toxic gases to different parts of the building as a function of time. The submodel also calculates the critical time when the stairs become untenable, which is considered to be the time when the occupants are trapped in the building. This critical time is used later by the evacuation duration submodel to calculate the time available for evacuation.

The fire detection submodel calculates the probabilities of detection at the first three detection times mentioned under the fire growth submodel, based on the probabilities of detection by smoke detectors, sprinklers, and occupants. This information is used by the occupant warning and response submodel to calculate the probabilities of response of the occupants.

The occupant warning and response submodel calculates the probabilities of warning and response at the first three detection times mentioned under the fire growth submodel. This information is used by the fire brigade action submodel to calculate the probability of response of the fire brigade, and by the egress submodel to model the evacuation of the occupants.

The fire brigade action submodel calculates the probability and time of arrival of the fire brigade. This submodel also evaluates the effectiveness of fire fighting, based on the flashover time from the fire growth submodel and the arrival time of the fire brigade. The information on arrival and effectiveness of the fire brigade is used by the smoke hazard submodel to calculate the maximum smoke hazard to the occupants, and by the fire spread submodel to calculate the probabilities of fire spread.

The smoke hazard submodel calculates the maximum smoke hazard to the occupants based on the burnout time from the fire growth submodel and the arrival time and effectiveness of the fire brigade from the fire brigade action submodel. This information is used by the life loss submodel to calculate the probabilities of life loss.

The evacuation duration submodel uses the three fire detection times from the fire growth submodel and the critical time in the stairs from the smoke movement submodel to calculate three durations available for evacuation. This information is used by the egress submodel to model the evacuation of the occupants.

Based on the evacuation time available and the probability of response of the occupants, this submodel calculates the number of occupants who have evacuated the building and the number trapped in the building. This information is used by the expected number of deaths submodel to calculate the expected number of deaths.

The boundary element submodel calculates the probabilities of failure of the boundary elements (walls, floors, doors, etc.) when they are subjected to fully developed, realistic fires. The submodel comprises the following probabilistic models: fire severity, temperature distribution, thermomechanical material properties, failure performance for each limit state, and overall probability of failure.

Based on the probabilities of failure of the boundary elements, this submodel calculates the probabilities of fire spread to each part of the building given a fully developed fire in any enclosure. A probabilistic network of the building is developed where nodes represent building volumes, links represent boundary elements between volumes, and probabilities of failure of the boundary elements are assigned to links. Allowance is made for the effectiveness of the fire brigade. The probability of fire spread information is used by both the property loss submodel and the life loss submodel to estimate fire losses and life loss.

Based on the probabilities of smoke hazard from the smoke hazard submodel and fire spread from the fire spread submodel, this submodel calculates the probabilities of life loss.

Based on the probabilities of life loss from the life loss submodel and the number of occupants trapped in the building from the egress submodel, this submodel calculates the expected number of deaths in the building.

Based on the probabilities of fire spread from the fire spread submodel, this submodel calculates the expected property loss.

Based on the expected property loss and the capital and maintenance costs of the fire protection systems, this submodel calculates the expected fire costs.

The expected risk-to-life submodel calculates the overall expected risk to life (ERL) by summing the expected number of deaths in the building for each fire scenario and the probability of each fire scenario.

The fire-cost expectation submodel calculates the fire-cost expectation (FCE) using the capital and maintenance costs of the fire protection systems, the expected fire loss for each fire scenario, and the probability of each fire scenario.

In the risk-cost assessment model, due to the complexity and the lack of sufficient understanding of fire phenomena and human behavior, certain conservative assumptions and approximations were made in the mathematical modeling. In addition, not all aspects of the risk-cost assessment model have been fully verified by full-scale fire experiments or actual fire experience. Only some of the submodels have been verified by experiments or statistical data.

As a result, the predictions made by the model can be considered as only approximate. The model, therefore, should not be used for absolute assessments of life risks and protection costs. For comparative assessments of life risks and protection costs, and for the selection of a cost-effective fire safety system design solution, the model is considered to be reliable.

As in many computer models, the model uses certain input parameters to describe the characteristics of various fire safety designs. These include the fire resistance rating of boundary elements, the reliability of smoke alarms and sprinklers, the probability of doors open or closed, and the response time of fire brigades. The sensitivity of these parameters on the predicted risks has been checked and found to be reasonable [112].

FRAMEworks

Another computer-based risk assessment model, *FRAMEworks*, was developed through a collaborative effort between the National Institute of Standards and Technology (NIST), the NFPA Fire Analysis & Research Division, and the private consulting firm of Benjamin/Clarke Associates [113, 114]. The goal of this effort was to develop an objective, comprehensive, generally applicable, and widely recognized fire risk assessment methodology for products that go into buildings. The result was a method for quantifying the fire risk associated with a specific class of products in a specified occupancy.

FRAMEworks is similar in many respects to the fire risk and cost assessment model of Beck described above. It combines a quantitative (fire effects modeling) method to evaluate specific products in specific fire scenarios with a statistical method of relating fire deaths to the specific scenarios in order to establish a death rate baseline for the scenarios. The impact of new or replacement products can then be evaluated against the baseline scenarios to determine if the risk is comparatively higher or lower with a change of product(s).

The modeling sequence to compute fire risk in *FRAMEworks* is illustrated in Fig. 75.14. A more detailed description of the model can be found in the NFPA *Fire Protection Handbook*® [114].

CRISP

A computer-based fire risk assessment model is also under development in the United Kingdom by the Building Research Establishment, Fire Research Station. This model, called CRISP (Computation of Risk Indices by Simulation Procedures), is similar to the Beck model in that it provides a Monte Carlo simulation of entire fire scenarios but is an object-oriented model as opposed to a state transition model [115, 116]. The basic concept of the CRISP approach is that the building-contents-people system is treated as a collection of objects, represented by a section of the program that defines the objects' behavior in response to stimuli (input data). The objects may interact in a number of ways, depending on the information exchanged between them, but data associated with an object cannot be changed by another object (only by changing that object's code). Thus, for any given scenario, the objects will interact with each other but not change each

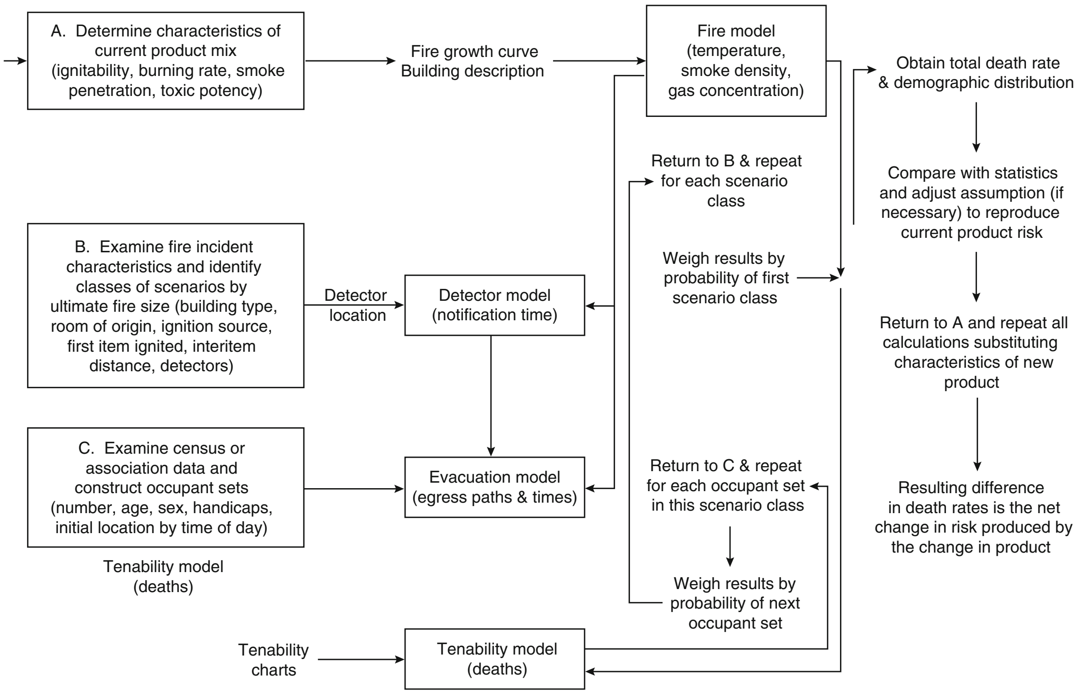


Fig. 75.14 Modeling sequence to compute fire risk in FRAMEworks [113]

other, based on the associated object definition and input parameters.

The types of objects modeled include furniture, hot and cold gas layers, vents, walls, rooms, alarms, occupants, and fire fighters [115]. The actions of the objects are governed by physical relationships (e.g., fire growth) and tables of rules (e.g., for people). For each run, various conditions, contents, and occupant characteristics are randomly selected and probabilities are assigned. Once the conditions have been defined, the simulation predicts how a scenario develops with time until the fire is out or the occupants are dead or have escaped.

Thus far, the scope of CRISP runs has been limited to two-story residential occupancies, and has been used to evaluate such trade-offs as fire detection installation versus the need for additional passive fire protection, and caution has been urged relative to the model's use in more complex buildings [105].

FRIM-MAB

A fire risk index method has been developed for multistory apartment buildings (FRIM-MAB) [117]. The approach uses a semiquantitative approach to characterize the fire risk associated with timber-frame buildings common within the Nordic countries of northern Europe.

Specific fire-related parameters such as apartment linings, smoke detection, escape routes, and the like are defined, with supporting decision tables to allow consistent evaluation of each parameter. The parameters are indexed based, for example, on the type of suppression system provided. The whole building is then assessed using a semiquantitative method. A comparative risk value is then determined for each building. This approach provides a consistent method for categorizing the risk within buildings. The approach has been supported by more complex modeling using quantified risk assessment

(QRA) techniques. The risk index provided has been shown to be consistent with the calculated expected risk from using QRA; however, it is noted the risk determined is not quantitative but provides valuable comparison between buildings assessed with the same method.

Of particular interest is the ability to provide repeatable and consistent evaluations of risk. The approach has been validated via assessment of separate buildings by independent engineers, evaluating the buildings with identical information. The results show, for the sample buildings assessed, that a consistent answer can be provided.

BuildingQRA

BuildingQRA [141] is a software package developed to help assess safety and financial risks associated with fires in buildings. An event tree structure is used. Scenarios are solved probabilistically for the event tree using Monte Carlo analysis. The software includes options assessment and cost-benefit prioritization. Multiple scenarios assessments are based either on discrete hazard (smoke) and egress analysis using zone models or user defined values. Specific event trees can be developed. Distributions are used for input parameters. Other user defined functions, including fault trees, are available as well.

B-RISK

B-RISK is a fire simulation model and software program comprising a fire risk simulator for generating probability distributions for relevant model outputs, given that the statistical distributions to key input parameters are assigned [142]. Central to B-RISK is an underlying deterministic fire zone model, BRANZFIRE [143], for which the physics have been expanded, and a new tools for users has been implemented which allows for a better understanding and description of the uncertainty and risk associated with fires in building enclosures. The B-RISK model may be used for both single deterministic runs as well as for multiple iterations of a scenario for the purpose of sensitivity analysis or for producing probabilistic descriptors of fire risk under defined conditions.

CUrisk

A quantified risk assessment (QRA) program is being developed at Carlton University, CUrisk [118], to evaluate the fire safety designs, predominantly for timber-framed commercial buildings. Risk, in this instance, is determined with the use of an overriding system model, providing an event tree, with supporting submodels used to determine fire growth and smoke movement, boundary failure and fire spread, occupant response and evacuation, and building cost and economic loss.

The model uses deterministic analysis of separate fire scenarios to calculate, for example, smoke temperatures and toxic smoke concentrations within the fire compartment and neighboring compartments. The approach uses an advanced occupant evacuation model to determine the time taken for occupants to evacuate including a “rule-based” behavior system and random procedures within the decision-making process.

The results provide the expected risk to life (ERL) and the expected risk injury (ERI), based on the tenability criteria to yield both death and also incapacitation. The expected annual financial cost of fire within the building can also be determined.

Structured Technical Analysis of Risks from Fire (STAR-Fire) and Simplified Approach to Fire Risk Assessment (SAFiRE) Methods

Structured Technical Analysis of Risks from Fire (STAR-Fire) [119] and Simplified Approach to Fire Risk Assessment (SAFiRE) methods [120] were first developed following analysis of the King’s Cross Underground Station fire. The approaches are based on the risk assessment methods first developed in the nuclear industry and further developed in the offshore and transport industries, modified to provide quantified fire risk assessment for the design of buildings. These methods can address life safety, property protection, and business continuity fire safety objectives, with selection dependent on user needs, and can be used for both new and existing buildings. To date, a large cross section of building types has been assessed using these methods, including retail, public, transport, education, and industrial facilities [58, 120, 121].

Generic fault and event trees, and balanced modeling of frequency and consequence, are used in each approach [121, 122]. Individual and societal risk to life can be assessed, and average or distributional representations of financial loss measures can be used, with results presented in either tables or FN curves. The outcomes can then be used for absolute risk assessment, using risk criteria agreed on by stakeholders, or, comparatively, benchmarking to the risk levels associated with a code compliant design or other agreed benchmark (the latter being the preferred approach).

In these methods, individual fire events are defined by their frequency and their consequences. Scenarios are defined by fault and event tree analysis, with Monte Carlo analysis of highly variable parameters (e.g., number of people in the building at the time of ignition). Input data include geometry of spaces and escape routes, fire growth, detection, occupant number, premovement time and velocity/flow, frequency of ignition, and probabilities of failure of fire protection systems, with probability distributions being calculated for the most variable parameters; and evacuation time, tenability time, and statistical analysis of some scenarios being generated. Simulation of one million fire scenarios requires on the order of 1–2 h. Uncertainty, safety factors, sensitivity, precision, and bias are addressed through a qualitative narrative.

Hazard and Risk Matrices

In addition to the more complicated single-scenario and ETA-based engineering approaches and computer-based risk modeling, various risk analysis alternatives exist that combine hazard analysis, consequence analysis, and judgments about likelihood of events in less quantitatively rigorous manners. This does not imply the methods are less rigorous, or less appropriate, but that they are simply easier to apply. In many cases, such simplified approaches will be more widely accepted by interested and affected parties, as the concepts may be familiar.

One such approach is the hazard matrix [123], or risk matrix approach [10, 124]. This approach is simpler to apply than a classical engineering risk analysis approach, as the importance of identifying all possible outcomes is less critical. In essence, it works by quantifying the consequences of the most severe events anticipated and coupling these with approximate event frequencies. The result is a quantified approximate risk estimate. In this approach, a maximum consequence for each type of loss is identified (life safety, property, business interruption, environmental damage, etc.) that represents the largest realistic event of each type. Each maximum consequence is then ranked. Table 75.3 provides an example of possible consequence ranking thresholds (i.e., negligible, low, medium, and high) that may be selected. For these estimates, the consequence predictions should bound all possible event outcomes at the 95th percentile or better [10]. The 95th percentile value is suggested because it has gained ready acceptance in other engineering fields, and by using such a standard value, it may be possible to compare different analyses. If it is desired to use a different bounding level, all stakeholders must agree. An extensive analysis can often be avoided when selecting the maximum consequence if the total replacement costs are assumed to be the maximum consequence.

The frequencies must also be ranked in this type of analysis. Here, the frequencies should be for exceeding a specific loss (i.e., consequence) rather than for a specific scenario, as frequencies based solely on a specific scenario can be misleading. For example, a scenario may have a frequency of 10^{-7} per year, leading one to the conclusion that fire is not a concern. However, the reported fire risk should actually represent

Table 75.3 Possible consequence ranking criteria [10]

Consequence level	Impact on populace	Impact on property/operations
High (H)	Immediate fatalities, acute injuries—immediately life threatening or permanently disabling	Damage > \$XX million—building destroyed and surrounding property damaged
Moderate (M)	Serious injuries, permanent disabilities, hospitalization required	\$YY < damage < \$XX million—major equipment destroyed, minor impact on surroundings
Low (L)	Minor injuries, no permanent disabilities, no hospitalization	Damage < \$YY—reparable damage to building, significant operational downtime, no impact on surroundings
Negligible (N)	Negligible injuries	Minor repairs to building required, minimal operational downtime

Table 75.4 Example frequency criteria used for probability ranking [10]

Acronym	Description	Frequency level (median time to event)	Description
A	Anticipated, expected	$>10^{-2}$/year (<100 years)	Common incidents that may occur several times during the lifetime of the building
U	Unlikely	$10^{-4} < f < 10^{-2}$/year (100–1,0000 years)	Events that are not anticipated to occur during the lifetime of the facility. Natural phenomena of this probability class include UBC-level earthquake, 100-year flood, maximum wind gust, etc.
EU	Extremely unlikely	$10^{-6} < f < 10^{-4}$/year (1,0000–1 million years)	Events that will probably not occur during the life cycle of the building
BEU	Beyond extremely unlikely	$<10^{-6}$/year (>1 million years)	All other accidents

the frequency of multiple fire scenarios, so if 30 specific scenarios are developed, each at 10^{-7} fires per year, the net effect is 3×10^{-6} fires per year. Table 75.4 provides a specific example for frequency ranking [10, 122]. As with consequence ranking, alternate frequency rankings (bins) from those presented in Table 75.4 can be developed provided that all interested and affected parties agree. It is also possible to add additional layers of ranking where desirable.

Once the bounding consequences and their respective frequencies have been estimated, they must be converted to an estimate of risk. An estimation is accomplished by plotting the consequence-frequency combination in a matrix, as shown in Fig. 75.15 (the numbers in boxes are for identification purposes and do not imply a ranking). The stakeholders assign each consequence-frequency combination, and the resultant risks are considered bounding risks. After this analysis, events that meet a certain risk criterion may be considered "acceptable" based on the objectives and input from the interested and affected parties (e.g., the interested and affected parties may consider moderate, low, and negligible risk events acceptable).

Performance Matrix

A concept similar to that of the hazard and risk matrices approach described above has been developed for use in building and fire safety regulations [1, 4, 5, 125–128]. This approach establishes a performance matrix that compares performance groups (building types grouped by like performance expectations) by magnitude of design events (probabilistic or deterministic descriptions of hazard event). Within the

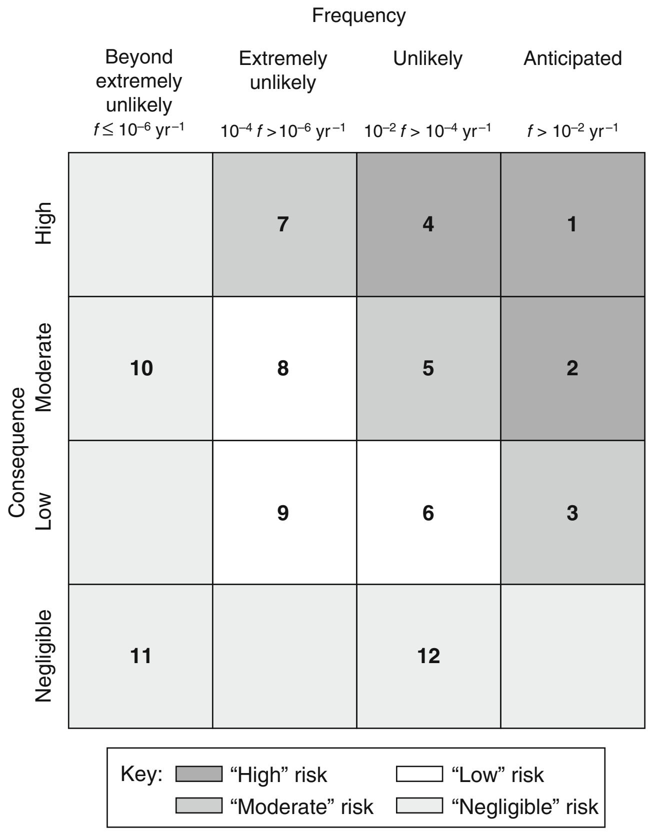


Fig. 75.15 Example risk ranking matrix [10]

performance matrix, instead of having risk bins (groups), there are tolerable levels of impact (reflecting the amount of damage expected for buildings within different performance groups given specific magnitudes of design events). As the performance group increases from Group I to Group IV, the level of required performance increases, as do the corresponding levels of tolerable impact. This is illustrated in Fig. 75.15.

Within the performance matrix, tolerable levels of impacts reflect various limit states of damage, injury, or loss that can be estimated, measured, and/or calculated when subjected to design loads of various magnitudes. As the impacts get larger, it is expected that more damage will occur, unless a higher level of performance is desired. In this manner, the levels of impact are inversely proportional to building performance: less impact means better performance. Establishment of these levels of tolerable impact requires a balance of technical knowledge and ability and societal values. The term *tolerable* is used to reflect the fact that absolute protection is not possible, and that some damage, injury, or loss is currently tolerated in structures, especially after a hazard event. The term *impact* is used as a broad descriptor of loss.

If one so chooses, one can overlay probabilities and consequences on the performance matrix in a manner similar to the hazard and risk matrices discussed previously. In the performance matrix (Fig. 75.16), the magnitudes of design event can be overlaid with probabilities (or frequencies) of event occurrence, from high at the bottom to low at the top. For all high-probability events, the allowable magnitude of impact (consequences) is either mild or moderate depending on the performance group. For low-probability events, the allowable magnitude of impact can be moderate, high, or severe depending on the performance group. This approach allows for decisions to be made on the required level of building performance for low-probability, high-consequence events, based on the performance group to which a building is designated.

Performance groups are simply consolidations of use groups with common performance requirements. They are developed as part of the risk characterization process, considering such issues as numbers of people in a building, sensitive or vulnerable populations, the hazards posed by the building, its contents or processes, and essential facilities and services [126]. The number of performance groups that is required should be based on an analytical-deliberative risk characterization process as described previously. The following definitions of performance groups represent one example, as used in the *International Performance Code for Buildings and Facilities* [125].

Performance Group I is intended to cover those buildings or facilities, such as utility sheds, where the failure of such buildings poses a low risk to human life. Performance Group II is intended to be the minimum for most typical buildings, such as business, mercantile, or storage uses. Performance Group III includes building and facilities with an increased level of societal benefit or importance. These structures and classes of structures require increased levels of performance as they house large numbers of people, vulnerable populations, or occupants with other risk factors; or they fulfill some role of increased importance to the local community or to society in general. Examples include post-disaster command control centers, acute-care hospitals, or a school used as an emergency shelter. Performance Group IV contains building uses or facilities that have an unusually high risk. Such facilities may include nuclear facilities or explosives storage facilities. For specific facilities, for specific jurisdictions, or in countries outside of the United States, other definitions for the performance groups may be appropriate.

Fig. 75.16 Performance matrix [1, 125]

		Increasing level of building performance Performance groups			
		Performance group I	Performance group II	Performance group III	Performance group IV
Magnitude of design event Increasing magnitude of event	Very large (very rare)	**Severe**	**Severe**	**High**	**Moderate**
	Large (rare)	**Severe**	**High**	**Moderate**	**Mild**
	Medium (less frequent)	**High**	**Moderate**	**Mild**	**Mild**
	Small (frequent)	**Moderate**	**Mild**	**Mild**	**Mild**

Likewise, the number of tolerable levels of impact can be selected based on the level of detail deemed appropriate by interested and affected parties. One possibility is the use of four levels: mild, moderate, high, and severe [128]. The definition of each level would reflect the tolerability limits as developed by a risk characterization effort. For example, a moderate level of impact may be defined as follows (remember that levels of impact are inversely proportional to levels of performance, and that these are design goals):

- There is moderate structural damage that is repairable; some delay in reoccupancy can be expected due to structural rehabilitation.
- Nonstructural systems needed for normal building use are fully operational, although some cleanup and repair may be needed. Emergency systems remain fully operational.
- Injuries to building occupants may be locally significant, but generally moderate in numbers and in nature. There is a low likelihood of single life loss and a very low likelihood of multiple life loss.
- Damage to building contents may be locally significant but is generally moderate in extent and cost.
- Some hazardous materials are released to the environment, but the risk to the community is minimal. No emergency relocation is necessary.

Associated with the tolerable levels of impact is the actual hazard event. One way to look at the hazard event is in terms of its size, or magnitude. The magnitude of a hazard event can be represented deterministically or as a frequency of occurrence. When characterizing the magnitude of hazard events, it is important to remember that (1) they are on a continuum and are compartmentalized for ease of analysis and design; and (2) they should be considered "design loads" and not as a reflection of the actual magnitude of event that could impact a building.

As with tolerable levels of impact, the number of magnitude of event levels can be established by the interested and affected parties. For example, four categories of event magnitude (design loads) can be selected: small (frequent), medium (occasional), large (rare), and very large (very rare). To understand how the magnitudes can be described, consider earthquake loads and fire loads, where earthquake loads are shown in terms of their mean return period, and fire loads are shown deterministically in terms of extent of flame spread.

Earthquake loads (mean return period)	
Frequent	72 years
Occasional	225 years
Rare	474 years
Very rare	2475 years
Fire loads (deterministic)	
Small	Contained to object of origin
Medium	Contained to room
Large	Contained to floor
Very large	Contained to building

There is often correlation between frequent, occasional, rare, and very rare; and small, medium, large, and very large; in that frequent events tend to be small, whereas very large events tend to be very rare. Also, it is often the very large or very rare events that are of particular concern, as it is these events for which providing high levels of protection against is costly and may not be considered reasonable or cost-effective for all buildings.

The Building Fire Safety Evaluation Method (BFSEM)

Another approach to identifying hazards and consequences, for obtaining judgments on the likelihood of events occurring, and for characterizing risk, is the *Building Fire Safety Evaluation Method* (BFSEM) [129–133]. The BFSEM can be used to analyze an existing building or a proposed new building. A primary goal is to understand how the building will perform for credible diagnostic fire scenarios. Describing expected risk characterizations are another part of a complete BFSEM analysis. One can perform either a holistic analysis or an individual component analysis.

Figure 75.17 illustrates the scope of fire performance and risk characterizations [132]. After one understands the building's performance and can characterize the associated risks, an integrated design or risk management program can be developed.

The system of building-fire behavior is dynamic. Therefore, time links all parts of the system. The method's organization provides a way to coordinate dynamic fire changes and fire defense operations. An analysis incorporates time-based changes in component performance by adapting conventional event trees of risk analysis. Performance evaluations for any instant of time adapt conventional fault tree analysis. Component interactions are incorporated into evaluations.

The method is based on deterministic analyses of the fire defense components. An analysis uses modules that are obtained by decomposing the complete functional system of fire and buildings and repackaging the components into analytical networks. Adapting techniques of failure analysis to additional decompositions provides a basis for evaluating events that are critical to performance.

Time-based relationships can be captured in an *Interactive Performance Information* (IPI) chart, which orders and records important information for performance evaluations and risk characterizations. It allows one to observe changes in any component over time as well as to examine the status of any or all components at any instant of time. An IPI chart is illustrated in Fig. 75.18 [132]. In Fig. 75.18, the diagnostic fire scenario and each of the major fire defense parts are shown by the horizontal rows. Each of these rows describes an event tree adapted from conventional risk analysis. The status of the events

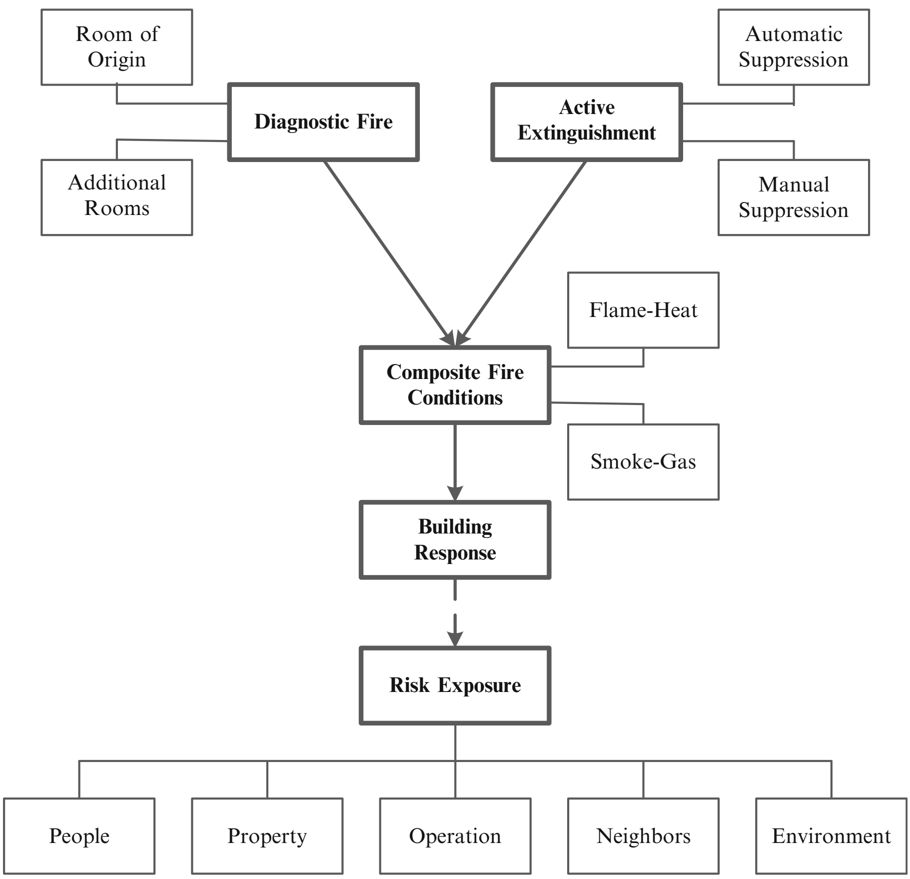


Fig. 75.17 Fire risk characterization in the BFSEM [132]

changes over the duration of the fire. The vertical columns identify time steps from ignition to extinguishment. The component events in a column are based on fault tree analysis.

The horizontal rows (event trees) are analogous to a continuous video of the operation of the major fire defenses and their major components. If we were to "stop the world" at an instant of time (i.e. examine the events in a single vertical column), the status of each component could be described and their interactions with other parts of the dynamic building-fire system would be recognized. This is analogous to examining a group of still photographs all taken at that time. For any fire scenario, each cell of the IPI chart is effectively a cell of a spreadsheet. A broad range of attributes, including a description of performance, can be shown for each instant of time.

A relatively narrow window of functional operation exists for each component of Fig. 75.18. One part of a performance analysis coordinates the time durations to understand the impact of functional operation sequencing for the building fire scenario. Each building has unique features that distinguish its fire performance from that of others. Thus, IPI charts provide a means to compare risks and the effectiveness of design improvements.

Performance quantification is deterministic. However, today's state of the art of fire technology is inadequate to quantify the performance of all components and their interactions. Consequently, evaluations incorporate Bayesian techniques to describe expected performance. This enables the contributions of other components at that instant of time to be incorporated into an evaluation. The process enriches performance understanding and communication by expressing results in terms of a probabilistic degree of success. This use of probability should not create the impression that the method is probabilistic. To the contrary, the method is deterministic, but uses Bayesian theory to bridge the gap between "benchmarks" of known behavior.

Application of the BFSEM provides a comprehensive method for identifying factors that affect the fire safety performance of a building. The method has been widely used, including being adapted by the U.S. Coast Guard to become its ship fire safety engineering methodology (SFSEM) [133].

Guidance Documents for Fire Risk Assessment

Given the growing interest in the use of risk assessment techniques for building fire safety evaluation, a number of organizations have prepared guidance documents that are useful to designers and approval authorities (i.e., AHJs) in relation to buildings.

These guides are not risk assessment methodologies or risk analysis techniques. Rather they are directed at assisting practitioners in selecting the appropriate methodology for any given building and ensuring that the process of risk assessment and approval is undertaken in a proper engineering manner.

SFPE Engineering Guide—Fire Risk Assessment

The *SFPE Engineering Guide*: *Fire Risk Assessment* [134] is aimed at those qualified practitioners undertaking design and evaluation of buildings and/or process fire safety. The document provides guidance on the selection and use of risk assessment techniques and provides a recommended process to follow.

The *SFPE Guide* does not specify particular risk assessment methods or techniques. However, it highlights

- A recommended process for fire risk assessment (Fig. 75.19)
- Tools that may be used for hazard identification
- Sources of data for risk assessment
- Approaches to consequence modeling
- Methods for calculating fire risk
- Documentation of fire risk assessment

The *SFPE Guide* is structured to follow the flowchart represented in Fig. 75.19, providing guidance and information association with each

Working IPI Template

		Section				Event	Time					
							1	5	10	15	20	25
Building Performance	Fire Response	1			$\bar{I}$	**Diagnostic Fire**						
			A		$\bar{I}_F$	**Flame-Heat**						
			B		$\bar{I}_S$	**Smoke-Gas**						
		2				**Active Extinguishment**						
			A		M	**Fire Department Extinguishment**						
				a	$M_{Part\ A}$	Part A: Ignition to Notification						
					MD	Detect Fire						
					MN	Notify Fire Department						
				b	$M_{Part\ B}$	Part B: Notification to Arrival						
					MS	Dispatch Responders						
					MR	Resonders Arrive						
				c	$M_{Part\ C}$	Part C: Arrival to Extinguishment						
					MA	Apply First Water						
					MC	Control Fire						
					ME	Extinguish Fire						
			B		A	**Automatic Sprinkler Suppression**						
				a	AA	Sprinkler System is Reliable						
				b	AC	Sprinkler system controls fire						
		3			L	**Composite Fire**						
			A		L_F	**Flame-Heat**						
			B		L_S	**Smoke-Gas**						
	Building	4			R	**Building Response**						
			A		St	**Structural Frame**						
			B		TS	**Target Space Tenability**						
Risk Characteristics		5			L	**Risk Characteristics**						
			A		LS	**People**						
			B		RP	**Property**						
			C		RO	**Operational Continuity**						
			D		RE	**Exposure Protection**						
			E		RN	**Environment**						

Fig. 75.18 Interactive Performance Information (IPI) chart representation of BFSEM [132]

step in the process. This information is supported with many references and a comprehensive list of information sources for further reading for each step of the risk assessment process. An overview of the SFPE process can be found in reference [135].

NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*

NFPA 551, *Guide for the Evaluation of Fire Risk Assessments* [136], was developed in the United States in recognition of the fact that fire risk assessment methods are increasingly being used in developing fire and life safety solutions for buildings and other facilities.

This guidance document is directed at those responsible for approving or evaluating fire and life safety solutions based on a fire risk assessment. It provides a framework that describes the properties of a fire risk assessment, particularly where it is being used in a performance-based regulatory framework. As a result, this guide is suited to a building or fire official or other authority having jurisdiction required to evaluate or approve a building design where the design is being supported by a fire risk assessment.

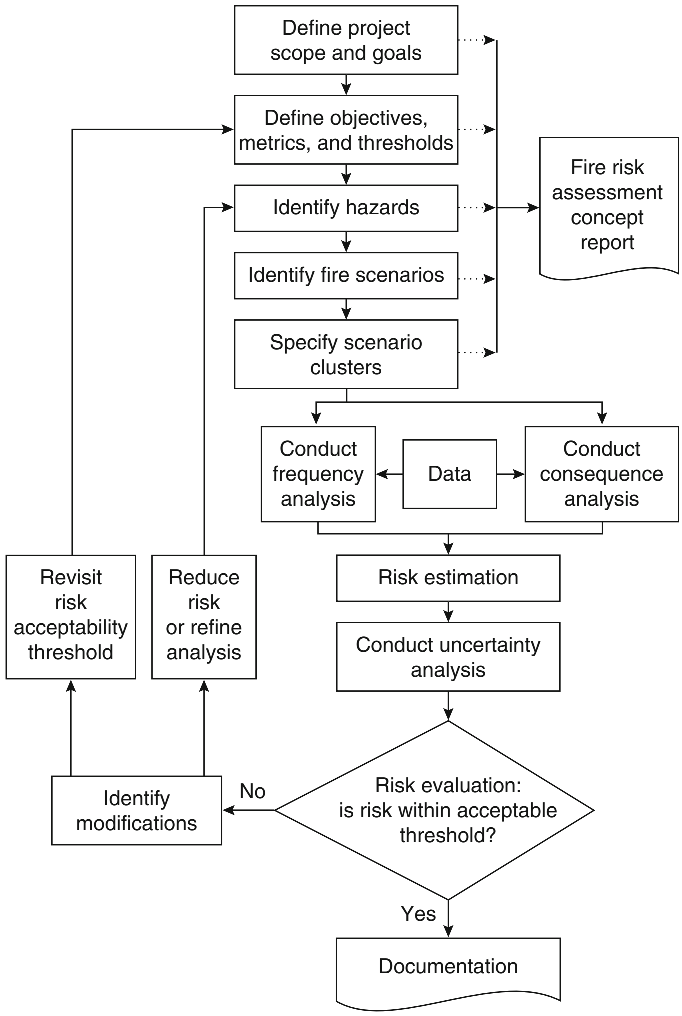


Fig. 75.19 Fire risk assessment flowchart [134]

Like the *SFPE Guide* referenced above, NFPA 551 neither specifies particular fire risk assessment methods nor attempts to set acceptance criteria. Rather it sets out the technical review process and documentation that should be used by those evaluating or approving. The review process is illustrated in Fig. 75.20.

NFPA 551 defines five categories of fire risk assessment methods in order of increasing complexity, namely

- Qualitative methods
- Semiqualitative criteria-based methods
- Semiqualitative consequence methods
- Quantitative methods
- Cost-benefit risk methods

It highlights the importance of identifying the objectives of any fire risk assessment and other factors that should be considered by those undertaking fire risk assessments. For each of the five categories of methods, the characteristics of each approach are identified, and issues of inputs and outputs, assumptions and limitations, selection of fire scenarios, and uncertainty are discussed.

BS 7974-7, *Probabilistic Risk Assessment*

The British Standards Institute (BSI), the National Standards Body of the United Kingdom (U.K.), provides a number of fire-related design standards. A framework for the application of fire safety engineering principles for the design of buildings is provided within BS 7974. This document is supported by the Published Document series PD 7974 Parts 0 to 7. The final document, Part 7, provides guidance for the probabilistic risk assessment of buildings [137].

The document provides a framework for risk assessment commensurate with a number of approaches within this handbook. Specifically, the document provides guidance with regard to acceptance criteria for life safety and financial assessments, which may use either comparative or absolute methodologies. The absolute criteria for individual risks and societal risk are provided. The logic tree is illustrated using both event trees and fault trees. An assessment methodology using *complex* analysis techniques is also provided, whereby risk is evaluated understanding the reliability of systems, use of stochastic models to evaluate the spread of fire within a building, Monte Carlo analysis used to evaluate a random distribution of variables addressing low-probability scenarios, and safety factors.

The annex to this document provides very useful guidance about the probability of fire starting dependent on the type and use of the building. Further, the average area damaged and the distribution of damage are provided. There are also valuable statistics on the frequency distribution of the numbers of deaths attributed to fire, the probability of flashover, and reliability data concerning active and passive fire safety systems.

These data are principally based on U.K. fire statistics recorded over a representative sample period and as such are considered a valuable

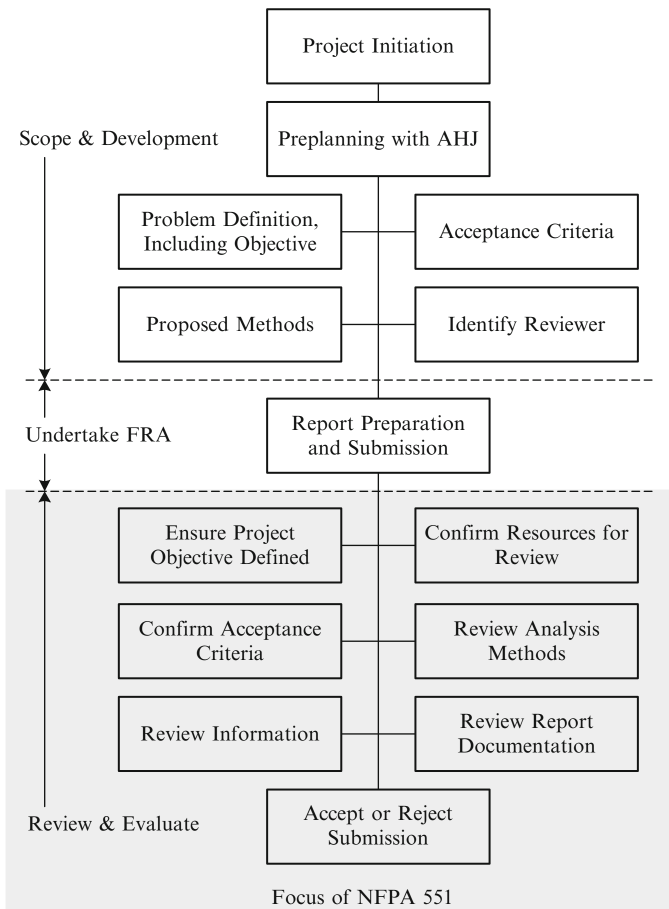


Fig. 75.20 NFPA 551 review process [136]

source of information, although generally applicable to U.K. projects. The data, for example, illustrate fire damage for an 8000-square-meter textile industry building is twice as large for a nonsprinkled building when compared to a sprinkler protected building.

ISO 16732-1:2012 *Fire Safety Engineering—Fire Risk Assessment*

ISO 16732-1:2012 provides the conceptual basis for fire risk assessment by stating the principles underlying the quantification and interpretation of fire-related risk [138]. The principles and concepts outlined in the standard can be applied to any fire safety objectives, including safety life, conservation of property, business continuity, preservation of heritage and protection of the environment. The fire risk principles discussed in the standard apply to all fire-related phenomena and user applications, which means that the principles can be applied to all types of fire scenarios.

In ISO 16732-1:2012, principles underlying the quantification of risk are presented in terms of the steps to be taken in conducting a fire risk assessment. These quantification steps are initially placed in the context of the overall management of fire risk and then explained within the context of fire safety engineering. The use of scenarios and the characterization of probability (or the closely related measure of frequency) and consequence are then described as steps in fire risk estimation, leading to the quantification of combined fire risk. Guidance is also provided on the use of the information generated, i.e., on the interpretation of fire risk. Finally, there is guidance on methods of uncertainty analysis, in which the uncertainty associated with the fire risk estimates is estimated and the implications of that uncertainty are interpreted and assessed.

As described by ISO 16732-1:2012, risk management includes risk assessment, but also typically includes risk treatment, risk acceptance, and risk communication (see Fig. 75.21).

In this approach, fire risk assessment is part of a larger process, which starts with setting fire risk goals and objectives, and where risk acceptance marks the conclusion of the assessment. If risk is not accepted, another risk assessment is necessary, and risk treatment is an option after each risk assessment. Risk communication is conducted after risk acceptance.

The component of fire risk assessment is defined as a procedure for estimation of fire risk for a built environment and evaluation of estimated fire risk in terms of well-defined acceptance criteria [138]. Fire risk assessment is can be used to quantify the risk associated with specific scenarios, but can also be used to assess alternative designs, prior to selecting a specific design or making changes to that design to achieve compliance with the acceptance criteria.

Fire risk assessment begins with the fire risk goals and objectives and a proposed design specification for the structure or other part of the built environment to be assessed. The risk associated with the design specification is estimated and then evaluated. Risk evaluation consists of comparison of the estimated risk for the design to the acceptance criteria.

Fire risk estimation begins with the establishment of a context. The context provides a number of quantitative assumptions, which are required with the objectives and the design specifications to perform the estimation calculations. Figure 75.22 describes the sequence of steps involved in fire risk estimation as it is conducted when the scenario structure is explicit and when frequencies and consequences are explicitly calculated in quantitative form (other sections of the standard describe the use of risk curves, risk matrices and other techniques for which the flow chart is not fully applicable in detail).

The standard goes on to describe in some detail the components in the fire risk estimation, as well as the role of uncertainty in the fire risk assessment process. Examples of application of fire risk assessment are also included.

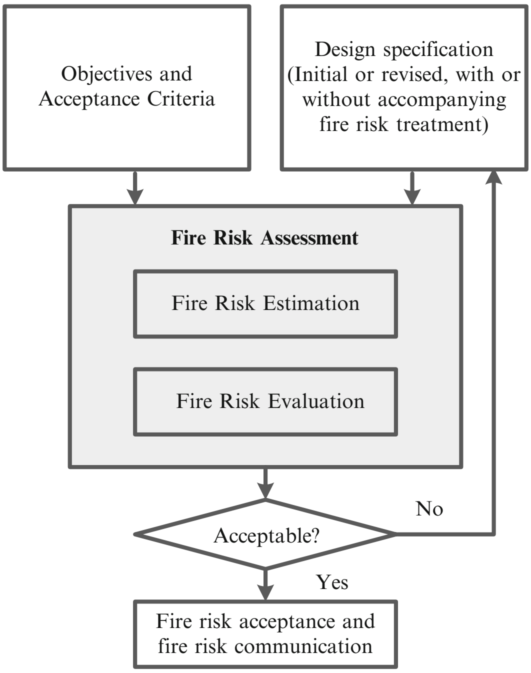


Fig. 75.21 Fire risk management concept [138]

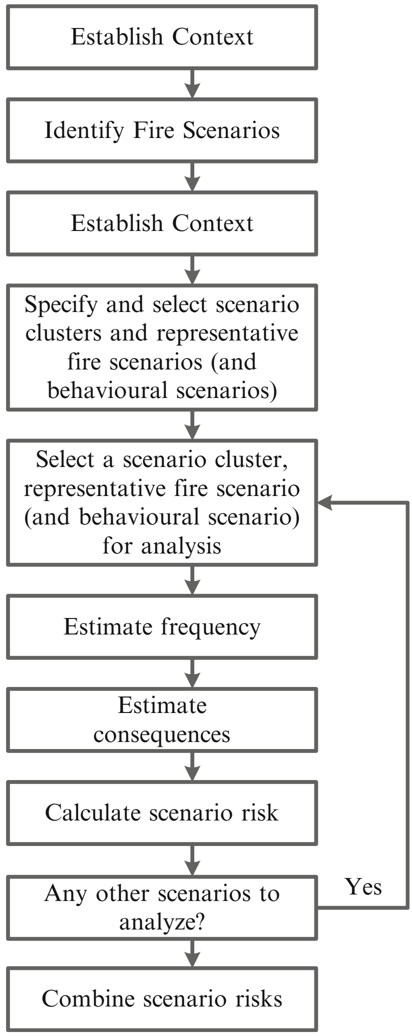


Fig. 75.22 Risk estimation [138]

Textbooks

As noted in the previous section, there has been a growing interest in fire risk assessment over the last two decades, which has prompted the development of several guidance documents and standards on fire risk assessment. In addition, there have been new chapters added to the SFPE Handbook on various aspects of fire risk assessment, e.g. by industry, occupancy type and sector (built environment, transportation), with each new edition. As another indicator of the growing interest in fire risk assessment, and the desire for information relative to tools and techniques for fire risk assessment, there have been a number of textbooks published in the last decade, with others in development. It is worth noting these as additional resource for fire protection engineers, with the hope that this section continues to expand in future editions.

Published in 2004, *Evaluation of Fire Safety* [139], while not strictly a text on fire risk assessment, includes many aspects of fire risk assessment throughout. Written by a collection of five leading authorities in fire safety engineering, the text includes chapters on sources of statistical fire loss data, measurements of fire risk, various fire risk evaluation methods (e.g., point systems, logic tress, stochastic fire risk modeling and the fire safety concepts tree and derivative approaches). It provides a comprehensive suite of information for anyone embarking on fire safety evaluation of the built environment.

Following the tragic events of September 11, 2001, the text *Extreme Event Mitigation in Buildings*: *Analysis and Design* [140] was published to provide a resource for understanding and assessing building performance under extreme events. While not focused solely on fire, the text provides information on assessing likelihood of occurrence, potential impacts, and strategies for mitigation for a wide range of extreme events—natural, technological and deliberate, while aiming to achieve a balance of acceptable levels of risk, performance and cost. The text outlines how risk-informed performance-based analyses can be used to help make important risk mitigation decisions.

In 2007, a trio of risk experts from Australia published the book, *Risk Analysis in Building Fire Safety Engineering* [94]. As the title implies, this text is focused on tools and techniques that are fundamental to applying risk concepts in fire safety engineering. It starts with elements of probability theory required for the understanding of risk analysis, then transitions into various tools for risk analysis, including the beta reliability index, Monte Carlo Analysis, Event Tree and Fault Tree analysis, and cost-benefit analysis. Several chapters are then provide relative to modeling the probabilistic and stochastic aspects of fire safety systems. Case studies are provided to illustrate the application of these concepts in performance-based fire safety design.

2008 saw the publication of a text focused on building fire risk assessment, *Principles of Fire Risk Assessment in Buildings* [96]. This text is presented in two parts: Part I overviews simple approaches to fire risk assessment, and Part II outlines a fundamental approach to fire risk assessment, considering fire growth, smoke spread, occupant response and other factors using fire risk assessment concepts. Like the text above, this was authored by an expert in the field who has developed models for fire risk assessment described earlier in this chapter.

Most recently, two renowned fire risk experts from the UK collaborated on the 2011 text, *Quantitative Risk Assessment in Fire Safety* [97]. This text presents a broad ranging discussion of qualitative, semi-quantitative and quantitative risk assessment techniques, discussing sources of data, structuring of the assessment technique, assessment and evaluation. Probabilistic and stochastic analysis of fire development and spread and response of fire safety systems is also provided. Reliability of fire safety systems, performance of people and effectiveness of the fire services is also presented.

These texts, as well as others written for specific industries, hazards and risks, provide fire protection engineers with additional resources for tackling the challenges of building fire risk analysis.

Summary

Building fire risk analysis is a complex subject. This chapter has provided a brief overview of key issues in the subject area, including discussions on difficulties in defining risk, on risk characterization, on tools and methods to help identify hazards and consequences, and on building fire risk analysis methods. Given the complexities involved in building fire risk analysis, it is intended that this chapter provide a starting point rather than an end point. With this in mind, extensive references and sources for further reading are provided for additional information. A review of other risk-related chapters in this handbook, such as those by Hall; Notarianni and Parry; Ramachandran and Hall; Watts; Barry; and Siu, Hyslop, and Nowlen is a good place to start. In addition, in the post-9/11 environment, building fire risk analysis should consider extreme fire and other events and be part of the overall risk assessment for the building [140]. Finally, it is important to remember that when embarking on a building fire risk analysis effort, one should take care to identify and involve the interested and affected stakeholders, carefully consider the range of risk issues involved, and seek the most appropriate approaches, tools, methods, and data for the problem.

References

1. B.J. Meacham, "A Process for Identifying, Characterizing, and Incorporating Risk Concepts into Performance-Based Building and Fire Regulations Development," Ph.D. Dissertation, Clark University, Worcester, MA (2000).

2. N.C. Rassmussen, "The Application of Probabilistic Risk Assessment Techniques to Energy Technologies," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 195–206 (1990).
3. P.C. Stern and H.V. Fineburg (eds.), *Understanding Risk: Informing Decisions in a Democratic Society,* National Academy Press, Washington, DC (1996).
4. B.J. Meacham, "Understanding Risk: Quantification, Perceptions and Characterization," *Journal of Fire Protection Engineering*, 14, 3, pp. 199–227 (2004).
5. B.J. Meacham, "Incorporating Risk Concepts into Performance-Based Building and Fire Regulation Development," in *Safety Engineering and Risk Analysis,* SERA Volume 9 (J.L. Boccio, ed.), American Society of Mechanical Engineers, New York, pp. 63–70 (1999).
6. B.J. Meacham, "Application of a Decision-Support Tool for Comparing and Ranking Risk Factors for Incorporation into Performance-Based Building Regulations," in *Proceedings of the Third International Conference on Performance-Based Codes and Fire Safety Design Methods,* SFPE, Bethesda, MD (2000).
7. B.J. Meacham and R.L.P. Custer, "Performance-Based Fire Safety Engineering: An Introduction of Basic Concepts," *Journal of Fire Protection Engineering,* 7, 2, pp. 35–54 (1995).
8. R.L.P. Custer and B.J. Meacham, *Introduction to Performance-Based Fire Safety,* NFPA, Quincy, MA (1997).
9. B.J. Meacham, "Assessment of the Technological Requirements for Realization of Performance-Based Fire Safety Design in the United States: Final Report," *NIST GCR 98-763,* NIST, Gaithersburg, MD (1998).
10. Society of Fire Protection Engineers, *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings,* SFPE and NFPA, Quincy, MA (2000).
11. R.L. Keeney and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs,* John Wiley and Sons, New York (1976).
12. R.L. Keeney, "Formal Analysis Including Value Judgments and Public Risk," *Toxic Substances Journal,* 3, 1, pp. 8–22 (1981).
13. R.T. Clemen, *Making Hard Decisions: An Introduction to Decision Analysis,* Duxbury Press, Pacific Grove, CA (1996).
14. R. Schwing and W. Albers (eds.), *Societal Risk Assessment: How Safe Is Safe Enough?,* Plenum, New York (1980).
15. E. Crouch and R. Wilson, *Risk/Benefit Analysis,* Ballinger Publishing Company, Cambridge, MA (1982).
16. R. Wilson, "Commentary: Risks and Their Acceptability," *Science, Technology and Human Values,* 9, 2, pp. 11–22 (1984).
17. D.J. Alesch and W.J. Petak, *The Politics and Economics of Earthquake Hazard Mitigation: Unreinforced Masonry Buildings in Southern California,* Institute on Environment and Behavior, University of Colorado, Boulder (1986).
18. S. Kelman, "Cost-Benefit Analysis: An Ethical Critique," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 129–137 (1990).
19. S. Breyer, *Breaking the Vicious Circle: Toward Effective Risk Regulation,* Harvard University Press, Cambridge, MA (1993).
20. T. O. Tengs et al., "Five Hundred Life-Saving Interventions and Their Cost-Effectiveness," *Risk Analysis,* 15, 3, pp. 369–390 (1995).
21. W.K. Viscusi and J.E. Aldy, "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World," *Related Publication 03-2,* AEI-Brookings Joint Center for Regulatory Studies (Jan. 2003).
22. H. Kunreuther and R.J. Roth, Sr., *Paying the Price: The Status and Role of Insurance Against Natural Disasters in the United States,* Joseph Henry Press, Washington, DC (1998).
23. P.R. Kleindorfer and H.C. Kunreuther, "The Complementary Roles of Mitigation and Insurance in Managing Catastrophic Risks," *Risk Analysis,* 19, 4, pp. 727–738 (1999).
24. *Guidelines for Chemical Process Quantitative Risk Analysis,* American Institute of Chemical Engineers, Center for Chemical Process Safety, New York (1985).
25. Health Facilities Note, HFN 09, "Fire Safety—Cost or Benefit?" Her Majesty's Stationery Office, London, UK (1995).
26. S.E. Magnusson, H. Franzich, and K. Harada, "Fire Safety Design Based on Calculations: Uncertainty Analysis and Safety Verification," *Report 3078,* Lund University, Lund, Sweden (1995).
27. S.E. Magnusson, H. Frantzich, K. Harada. "Fire Safety Design Based on Calculations: Uncertainty Analysis and Safety Verification," *Fire Safety Journal*, 27: 305–334, 1996.
28. H. Frantzich, "Uncertainty and Risk Analysis in Fire Safety Engineering," *Report LUTVDG/(TVBB-1016),* Lund University, Lund, Sweden (1998).
29. D.A. Charters et al., "Assessment of the Probabilities That Staff and/or Patients Will Detect Fires in Hospitals," *Proceedings of the Fifth International Symposium of Fire Safety Science,* Melbourne, Australia (1997).
30. D.A. Charters, "Quantified Assessment of Hospital Fire Risks," *Proceedings of Interflam'96,* InterScience Communications, Cambridge, UK (1996).
31. N. Groner, "A Critique of Event Modeling as Applied to Human Reliability and a Suggested Alternative," in *Proceedings of the SFPE Symposium on Risk, Uncertainty and Reliability in Fire Protection*

Engineering, SFPE, Bethesda, MD, pp. 190–199 (1999).

32. R.E. Britter, "The Evaluation of Technical Models Used for Major-Accident Hazard Installations," *EUR 14774EN,* Commission of the European Communities, Brussels, Belgium (1993).
33. C. Hohenemser, R. Kasperson, and R.W. Kates, "Causal Structure," in *Perilous Progress: Managing the Hazards of Technology (*Kates, Hohenemser, and Kasperson, eds.), Westview Press, Boulder, CO, pp. 25–42 (1985).
34. M.C. White et al., "A Quantitative Estimate of Leukemia Mortality Associated with Occupational Exposure to Benzene," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 165–180 (1990).
35. B.N. Ames, R. Magow, and L.S. Gold, "Ranking Possible Carcinogenic Hazards," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 76–99 (1990).
36. D. Hattis and D. Kennedy, "Assessing Risks from Health Hazards: An Imperfect Science," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 156–163 (1990).
37. B.D. Goldstein, *Issues in Risk Assessment,* National Research Council, National Academy Press, Washington, DC (1993).
38. C.T. Petito and B.D. Beck, "Evaluation of Evidence of Nonlinearities in the Dose-Response Curve for Arsenic Carcinogenesis," *Trace Substances in Environmental Health,* 24, pp. 143–176 (1990).
39. F.P. Lees, *Loss Prevention in the Process Industries,* Butterworths, London (1980).
40. R.L. Keeney et al., "Assessing the Risk of an LNG Terminal," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 207–217 (1990).
41. G. Apostolakis, "Fire Risk Assessment and Management in Nuclear Power Plants," *Fire Science and Technology,* 13, Supplement, pp. 12–39 (1993).
42. Y.Y. Haimes, *Risk Modeling, Assessment, and Management,* John Wiley and Sons, New York (1998).
43. Proceedings of the SFPE Symposium on Risk, Uncertainty and Reliability in Fire Protection Engineering and Joint SFPE/UMD/Clark University Workshop on Encouraging the Use of Risk Concepts in Performance-Based Building and Fire Regulation Development, SFPE, Bethesda, MD (1999).
44. NFPA 550, *Guide to the Fire Safety Concepts Tree,* National Fire Protection Association, Quincy, MA, 2002 edition.
45. J.M. Watts, Jr., "Systems Approach to Fire-Safe Building Design," in *Fire Protection Handbook,* 20th ed. (A.E. Cote et al., eds.), National Fire Protection Association, Quincy, MA, pp. 1-157–1-170 (2008).
46. Random House, *The Random House College Dictionary,* Random House, Inc., New York (1980).
47. J.R. Hall, Jr., "Probability Concepts," in *SFPE Handbook of Fire Protection Engineering,* 3rd ed. (P.J. DiNenno et al., eds.), National Fire Protection Association, Quincy, MA, pp. 1-182–1-192 (2002).
48. G. Apostolakis, "Probability and Risk Assessment: The Subjectivistic Viewpoint and Some Suggestions," *Nuclear Safety,* 19, 3, pp. 305–315 (1978).
49. M.J. Karter, Jr., "1996 U.S. Fire Loss," *NFPA Journal,* 91, 5, pp. 77–83 (1997).
50. M. Fontana, J.P. Favre, and C. Fetz, "A Survey of 40,000 Building Fires in Switzerland," *Fire Safety Journal,* 32, 2, pp. 137–159 (1999).
51. J. Rahikainen and O. Keski-Rahkonen, "Determination of Ignition Frequency of Fire in Different Premises in Finland," *Fire Engineers Journal,* 58, 197, pp. 33–37 (1998).
52. J.R. Hall, Jr., *The U.S. Fire Problem Overview Report—Leading Causes and Other Patterns and Trends,* National Fire Protection Association, Quincy, MA (1998).
53. *Fire in the United States, 10th Edition, 1986–1995,* National Fire Center, United States Fire Administration, Federal Emergency Management Agency, Emmitsburg, MD (1998).
54. *Fire Safety Engineering in Buildings,* British Standards Institute, DD 240: Parts 1 and 2 (1997).
55. Fire Code Reform Centre, *Fire Engineering Guidelines,* Sydney, Australia (1996).
56. D. Charters, C. Sherwood and E. Warren, (2012), "A Study of the nature of fire risks in tall buildings," Proceedings, 9th International Conference on Performance-Based Codes and fire Safety Design Methods. SFPE, Bethesda, MD.
57. Y. Kobayashi and H. Nozaki, (2005), "A Statistical Method to Evaluate Fire Risks in Non-Residential Buildings in Japan," Fire Safety Science: Proceedings of the Eight International Symposium, China, International Association for Fire Safety Science, pp. 341-352
58. J. Taveau (2010), "Risk assessment and land-use planning regulations in France following the AZF disaster," Journal of Loss Prevention in the Process Industries, Volume 23, issue 6, November 2010, pp. 813–823
59. K. Tillander (2004). *Utilisation of statistics to assess fire risk in buildings*, VTT Publications 537, VTT, Espoo, Finland.
60. M. Tsujimoto (2006), "Death risk by building fires in Japan and its usage," Fire Science and Technology, vol. 25, no. 2, pp. 63–68
61. F.R. Farmer, "Siting Criteria—A New Approach," *IAEA Symposium on the Containment and Siting of Nuclear Power Reactors, IAEA SM-89/34,* Vienna, Austria (Apr. 3–7, 1967).
62. D.P. Fernandes-Russell, "Societal Risk Estimates from Historical Data for UK and Worldwide Events," *Research Report No. 3,* Environmental

Risk Assessment Unit, University of East Anglia, UK (1987).

63. D. Charters, M. Salisbury, and S. Wu, “The Development of Risk-Informed Performance-Based Codes,” *Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods,* Society of Fire Protection Engineers, Luxembourg (2004).
64. F.R. Allen, A.R. Garlick, M.R. Hayns, and A.R. Taig, *The Management of Risk to Society from Potential Accidents,* Elsevier Applied Science, London (1992).
65. D.A. Charters, *Fire Safety Assessment of Bus Transportation,* AEA Technology, Warrington, UK, C437/037 (1992).
66. D. Kahneman and A. Tversky, “Judgment Under Uncertainty: Heuristics and Biases,” *Science,* 185, pp. 1124–1131 (1974).
67. W.W. Lowrance, *Of Acceptable Risk,* William Kaufmann, Inc., Los Altos, CA (1976).
68. B. Fischhoff et al., *Acceptable Risk,* Cambridge University Press, New York (1981).
69. P. Slovic, “Perception of Risk,” *Science,* 236, pp. 280–285 (1987).
70. V.T. Covello et al. (eds.), *Uncertainty in Risk Assessment, Risk Management, and Decision Making,* Plenum Press, New York (1987).
71. M.G. Morgan and M. Henrion, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis,* Cambridge Press, Cambridge, UK (1990).
72. S.O. Funtowicz and J.R. Ravetz, “Three Types of Risk Assessment and the Emergence of Post-Normal Science,” in *Social Theories of Risk* (Krimsky and Golding, eds.), Praeger, Westport, CT, pp. 251–274 (1992).
73. D. Hattis and D.E. Burmaster, “Assessment of Variability and Uncertainty Distributions for Practical Risk Analysis,” *Risk Analysis,* 14, 5, pp. 713–730 (1994).
74. F.O. Hoffman and J.S. Hammonds, “Propagation of Uncertainty in Risk Assessment: The Need to Distinguish Between Uncertainty Due to Lack of Knowledge and Uncertainty Due to Variability,” *Risk Analysis,* 14, 5, pp. 707–712 (1994).
75. M.W. Merkhofer, A Comparative Evaluation of Quantitative Decision-Making Approaches, SRI International, Menlo Park, CA (1983).
76. M.W. Merkhofer, “Comparative Analysis of Formal Decision-Making Approaches,” in *Risk Evaluation and Management* (V.T. Covello et al., eds.), Plenum Press, New York, pp. 183–220 (1986).
77. D.E. Bell, H. Raiffa, and A. Tversky (eds.), *Decision Making: Descriptive, Normative, and Prescriptive Interactions,* Cambridge University Press, Cambridge, UK (1988).
78. D. Hattis and E. Anderson, “What Should Be the Implications of Uncertainty, Variability, and Inherent Biases/Conservatism for Risk Management Decision Making?” Paper presented at *Second Workshop on When and How Can You Specify a Probability Distribution if You Don’t Know Much,* University of Virginia, Charlottesville (1997).
79. J.L. Casti, *Searching for Certainty: What Scientists Can Know About the Future,* William Morrow and Company, New York (1990).
80. V. Brannigan et al., “Risk Models Involving Human Decisions: Intentional Uncertainty and the Need for Regulation,” *Proceedings of the Second International Conference on Fire Research and Engineering,* SFPE, Bethesda, MD, pp. 252–262 (1998).
81. V.M. Brannigan and C. Smidts, “Performance-Based Fire Safety Regulation Under Intentional Uncertainty,” in *Proceedings of the 1st International Symposium on Human Behavior in Fire,* University of Ulster, Jordanstown, Northern Ireland, pp. 411–420 (1998).
82. J.R. Benjamin and C.A. Cornell, *Probabilities, Statistics, and Decision for Civil Engineers,* McGraw-Hill, New York (1970).
83. D. Von Winterfeldt and W. Edwards, *Decision Analysis and Behavioral Research,* Cambridge University Press, Cambridge, UK (1986).
84. G.S. Omenn et al., *Risk Assessment and Risk Management in Regulatory Decision-Making,* Presidential/Congressional Commission on Risk Assessment and Risk Management, Final Report, Volume 2, Washington, DC (1997).
85. K.A. Notarianni and P. Fischbeck, “Dealing with Uncertainty to Improve Regulations,” in *Proceedings of the 1999 Conference on Fire Design in the 21st Century,* SFPE and WPI, Worcester, MA (1999).
86. K.A. Notarianni, “The Role of Uncertainty in Improving Fire Protection Regulations,” Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh, PA (2000).
87. D.A. Lucht, “Public Policy and Performance-Based Engineering,” in *Proceedings of the International Conference on Performance-Based Codes and Fire Safety Design Methods,* SFPE, Bethesda, MD (1997).
88. B.J. Meacham, “Identifying and Addressing Uncertainty in Fire Protection Engineering,” in *Proceedings of the 2nd International Conference on Fire Research and Engineering,* SFPE, Bethesda, MD, pp. 238–251 (1998).
89. Albrecht, C. *A risk-informed and performance-based life safety concept in case of fire,* PhD thesis, TU Braunschweig, ISBN 978-3-89288-202-2, 2012.
90. Albrecht, C., Hosser, D., “A Response Surface Methodology for Probabilistic Life Safety Analysis using Advanced Fire Engineering Tools.” *Fire Safety Science* 10: 1059–1072, 2011.
91. M. Siemon, C. Albrecht and D. Hosser, “Considerations for the development of a quantitative life safety design concept using performance based fire engineering methods’,” *Proceedings of the 9th International SFPE-Conference on Performance- Based Codes and Fire Safety Design Methods*, SFPE, Bethesda, MD, USA, 2012.

92. P. Lancaster and K. Salkauskas, "Surfaces generated by moving least squares methods," *Mathematics of Computation*, 37(155):141–158, 1981.
93. T. Most and C. Bucher, "New concepts for Moving least squares: An interpolating non-singular weighting function and weighted nodal least squares," *Engineering Analysis with Boundary Elements*, 32:461–470, 2008.
94. A.M. Hasofer, V.R. Beck, and I.D. Bennetts, *Risk Analysis in Building Fire Safety Engineering*, Butterworth-Heinemann, Oxford, England, 2007, p 87.
95. C. Bucher, "Adaptive sampling-an iterative fast Monte Carlo procedure," *Structural Safety*, 5 (2):119–126, 1988.
96. D. Yung, Principles of Fire Risk Assessment in Buildings, John Wiley & Sons Ltd, Chichester, England, 2008.
97. G. Ramachandran and D. Charters, *Quantitative Risk Assessment in Fire Safety*, Spon Press, London, England (2011)
98. BS7974, Application of fire safety engineering principles to the design of buildings. Code of practice. Technical report, British Standards Institution (BSI), 2001.
99. C. Albrecht and D. Hosser, "A risk-informed framework for performance-based structural fire protection according to the Eurocode fire parts," Proceedings, *Interflam 9*, Interscience Communications, Ltd, UK, 2010.
100. V.R. Beck, "Cost-Effective Fire Safety and Protection Design Requirements for Buildings," Ph.D. Dissertation, University of New South Wales, Australia (1986).
101. V.R. Beck, "A Cost-Effective Decision-Making Model for Building Fire Safety and Protection," *Fire Safety Journal,* 12, pp. 121–138 (1987).
102. V.R. Beck, "Performance-Based Fire Engineering Design and Its Application in Australia," in *Fire Safety Science—Proceedings of the Fifth International Symposium,* IAFSS, Bethesda, MD, pp. 23–40 (1997).
103. V.R. Beck and D. Yung, "A Cost-Effective Risk Assessment Model for Evaluating Fire Safety and Protection in Canadian Apartment Buildings," *Journal of Fire Protection Engineering,* 2, 3, pp. 65–74 (1990).
104. D. Yung, G.V. Hadjisophocleous, and H. Takeda, "Comparative Risk Assessments of 3-Storey Wood-Frame and Masonry Construction Office Buildings," in *Proceedings of Interflam'93,* Interscience Communications Ltd., London, pp. 499–508 (1993).
105. V.R. Beck and S.L. Poon, "Results from a Cost-Effective Decision-Making Model for Building Fire Safety and Protection," *Fire Safety Journal,* 13, pp. 197–210 (1988).
106. V.R. Beck and D. Yung, "A Cost-Effective Risk Assessment Model for Evaluating Fire Safety and Protection in Canadian Apartment Buildings," *International Fire Protection Engineering Institute, 5th Conference,* Ottawa, Canada (1989).
107. V.R. Beck and D. Yung, "A Risk-Cost Assessment Model for Evaluating Fire Risks and Protection in Apartment Buildings," in *Proceedings of the International Symposium on Fire Engineering for Buildings and Structures,* The Institution of Engineers, Melbourne, Australia (1989).
108. I. Thomas, D.W. Weinert, and B. Ashe, "Quantified Levels of Risk to Life Safety in Deemed-to-Satisfy Apartment Buildings," in *8th International Symposium on Fire Safety Science,* IAFSS, Beijing, China (Sept. 2005).
109. J. Gaskin and D. Yung, "Canadian and U.S.A. Fire Statistics for Use in the Risk-Cost Assessment Model," *IRC Internal Report No. 637,* National Research Council, Ottawa, Canada (1993).
110. H. Takeda and D. Yung, "Simplified Fire Growth Models for Risk-Cost Assessment in Apartment Buildings," *Journal of Fire Protection Engineering,* 4, 2, pp. 53–66 (1992).
111. G.V. Hadjisophocleous and D. Yung, "A Model for Calculating the Probabilities of Smoke Hazard from Fires in Multi-Storey Buildings," *Journal of Fire Protection Engineering,* 4, 2, pp. 67–80 (1992).
112. G.V. Hadjisophocleous and D. Yung, "Parametric Study of the NRCC Fire Risk-Cost Assessment Model for Apartment and Office Buildings," *Proceedings of the 4th International Symposium on Fire Safety Science,* IAFSS, Bethesda, MD, pp. 829–840 (1994).
113. R.W. Bukowski, F.B. Clarke, J.R. Hall, Jr., and S.W. Stiefel, *Fire Risk Assessment Method: Description of Methodology,* National Fire Protection Research Foundation, Quincy, MA (1990).
114. J.R. Hall, Jr., "Product Fire Risk," in *SFPE Handbook of Fire Protection Engineering,* 3rd ed. (P.J. DiNenno et al., eds.), National Fire Protection Association, Quincy, MA, pp. 5-143–5-152 (2002).
115. J. Fraser-Mitchell, "An Object-Oriented Simulation (CRISP II) for Fire Risk Assessment," in *Fire Safety Science: Proceedings of the Fourth International Symposium,* IAFSS, Bethesda, MD, pp. 793–803 (1994).
116. J. Fraser-Mitchell, "Risk Assessment of Factors Related to Fire Protection in Dwellings," in *Fire Safety Science: Proceedings of the Fifth International Symposium,* IAFSS, Bethesda, MD, pp. 631–642 (1997).
117. Bjorn Karlsson, Iceland Fire Authority, Reykjavik, Iceland; Bodvar Tomasson, Linuhonnun Consulting Engineers, Reykjavik, Iceland. B. Karlsson, and B. Tomasson, "Repeatability Tests of a Fire Risk Index Method for Multi-Storey Apartment Buildings," *8th International Symposium on Fire Safety Science,* IAFSS, Beijing, China (Sept. 2005).
118. G. Hadjisophocleous and Z. Fu, "Development and Case Study of a Risk Assessment Model CUrisk for

Building Fires," *8th International Symposium on Fire Safety Science,* IAFSS, Beijing, China (Sept. 2005).
119. D.A. Charters and D. Berry, "Application of Quantified Fire Risk Assessment in the Design of Buildings," *Proceedings of Interflam '99,* Interscience Communications Ltd., London (1999).
120. D. Charters and S. Wu, "The Application of 'Simplified' Quantitative Fire Risk Assessment to Major Transport Infrastructure," SFPE Symposium on Risk, New Orleans (2002).
121. D. Charters, J. Paveley, and F.B. Steffensen, "Quantified Fire Risk Assessment in the Design of a Major Multi-Occupancy Building," in *Proceedings of Interflam 2001,* Interscience Communications Ltd, Edinburgh, UK (2001).
122. D. Charters, "What Does Quantified Fire Risk Assessment Need to do to Become an Integral Part of Design Decision-Making," SFPE International Conference on Performance Based Codes, San Francisco (2000).
123. System Safety Program Requirements, Military Standard 882C, U.S. Department of Defense, Washington, DC (1993).
124. *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports, DOE-STD-3009-94,* U.S. Department of Energy, Washington, DC (1994).
125. *International Code Council Performance Code for Buildings and Facilities,* International Code Council, Falls Church, VA (2012).
126. B.J. Meacham, "Application of a Decision-Support Tool for Comparing and Ranking Risk Factors for Incorporation into Performance-Based Building Regulations," *Proceedings, 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods*, SFPE, Bethesda, MD, 2000, pp. 59–70.
127. B.J. Meacham, "Identifying and Regulating for Multiple Levels of Performance," in *Proceedings of the International Council for Building Research and Innovation, World Congress—Wellington, NZ,* CIB, the Netherlands (Apr. 2001).
128. B.J. Meacham, "Performance-Based Building Regulatory Systems: Structure, Hierarchy and Linkages," *Journal of the Structural Engineering Society of New Zealand*, Vol. 17, No. 1, pp. 37–51, 2004.
129. R.W. Fitzgerald, "An Engineering Method for Building Fire Safety Analysis," *Fire Safety Journal,* 9, 2, pp. 233–243 (1985).
130. R.W. Fitzgerald, "An Engineering Method for Translating Fire Science into Building Design," in *Proceedings of the CIB W14 International Symposium and Workshops, Engineering Fire Safety in the Process of Design: Demonstrating Equivalency,* University of Ulster, Jordanstown, Northern Ireland (1993b).
131. R.W. Fitzgerald, *Building Fire Performance Analysis,* John Wiley & Sons, Chichester, UK, 2004.
132. Fitzgerald, R.W. and Meacham, B.J., *Fire Performance Analysis of Buildings,* John Wiley & Sons, Chichester, UK, in development, target publication May 2016.
133. R.W. Fitzgerald, R.C. Richards, and C.L. Beyler, "Fire Analysis of the Polar Icebreaker Replacement Design," *Journal of Fire Protection Engineering,* 3, 4, pp. 137–150 (1991).
134. Society of Fire Protection Engineers, *SFPE Engineering Guide: Fire Risk Assessment,* Society of Fire Protection Engineers, Bethesda, MD (Nov. 2006).
135. John Hall Jr. and A. Sekizawa, "Revisiting Our 1991 Paper on Fire Risk Assessment," *Fire Technology*, 46, pp 789–901, (2010).
136. NFPA 551, *Guide for the Evaluation of Fire Risk Assessments,* National Fire Protection Association, Quincy, MA, 2004 edition.
137. BS 7974-7, "Part 7—Probabilistic Risk Assessment," *Code on the Application of Fire Safety Engineering Principles to the Design of Buildings,* British Standards Institute, London, UK (2003).
138. ISO/PDTS 16732, *Fire Safety Engineering—Guidance on Fire Risk Assessment,* International Organization for Standardization (ISO), Geneva, Switzerland (2004).
139. D. Rasbash, G. Ramachandran, B. Kandola, J. Watts and M. Law, *Evaluation of Fire Safety*, John Wiley & Sons Ltd, Chichester, England, 2004.
140. B.J. Meacham, "Extreme Event Mitigation Through Risk-Informed Performance-Based Analysis and Design," in *Extreme Event Mitigation in Buildings: Analysis and Design* (B.J. Meacham and M.A. Johann, eds.), National Fire Protection Association, Quincy, MA, Chapter 2 (Apr. 2006).
141. *BuildingQRA*, Quantified Fire Risk Assessment Software for the Built Environment, Salisbury Fire Engineering Software, (www.fire-engineering-software.com), 2015.
142. C. Wade, G. Baker, K. Frank, A. Robbins, R. Harrison, M. Spearpoint, and C. Fleischmann. *B-RISK User Guide and Technical Manual*, BRANZ Study Report 282, BRANZ Ltd, Porirua, New Zealand (2013).
143. C.A. Wade. *BRANZFIRE Technical Reference Guide (revised)*, BRANZ Ltd, Porirua, New Zealand (2004).

Further Readings

C. Albrecht, "Quantifying life safety: Part I: Scenario-based quantification," *Fire Safety Journal*, doi:10.1016/j.firesaf.2014.01.003, Volume 64, Pages 87–94 (2014).

C. Albrecht, "Quantifying life safety: Part II: Quantification of fire protection systems," *Fire Safety Journal*, doi:10.1016/j.firesaf.2014.01.002, Volume 64, Pages 81–86 (2014).

V. Babrauskas, “Ensuring the Public’s Right to Adequate Fire Safety Under Performance-Based Building Codes,” in Proceedings of the 1998 Pacific Rim Conference and Second International Conference on Performance-Based Codes and Fire Safety Design Methods, ICBO and SFPE, Whittier, CA, pp. 239–247 (1998).

M.S. Baram, *Alternatives to Regulation: Managing Risks to Health, Safety and the Environment,* Lexington Books, Lexington, MA (1982).

V. Beck et al., *Fire Safety and Engineering Project Report,* The Warren Center for Advanced Engineering, Sydney, Australia (1989).

V.R. Beck et al., “Microeconomic Reform: Fire Regulation,” *National Building Fire Safety Systems Code,* in Building Regulation Review Task Force, Department of Industry Technology and Commerce, Canberra, Australia, p. 165 (1991).

M. Belsham, “Probable Cause,” *Fire Risk Management*, p. 41–46, February 2009.

V.M. Brannigan and A. Kilpatrick, “Performance-Based Codes: Reengineering the Regulatory System,” in *Proceedings of the International Conference on Performance-Based Codes and Fire Safety Design Methods,* SFPE, Bethesda, MD, pp. 139–149 (1997).

H.S. Brown and R.L. Goble, “The Role of Scientists in Risk Assessment,” *Risk: Issues in Health and Safety,* 1, 4, pp. 283–311 (1990).

D. Canter (ed.), *Fires and Human Behavior,* 2nd ed., Fulton Publishers, Ltd., London (1990).

R.E. Cheit, *Setting Safety Standards: Regulation in the Public and Private Sectors,* University of California Press, Berkeley, CA (1990).

G.Q. Chu, T. Chen, Z.H Sun, and J.H. Sun, “Probabilistic Risk Assessment for Evacuees in Building Fires,” *Building and Environment*, 42:1283–1290, 2007.

G. Chu and J. Sun, “Quantitative Assessment of Building Fire Risk to Life Safety,” *Risk Analysis*, DOI: 10.1111/j.1539-6924.2008.01048.x, Volume 28, Issue 3, pages 615–625 (2008).

G. Chu, J. Sun, “Decision analysis on fire safety design based on evaluating building fire risk to life,” *Safety Science*, doi:10.1016/j.ssci.2007.06.011, Volume 46, Issue 7, Pages 1125–1136 (2008).

V.T. Covello et al. (eds.), *The Analysis of Actual versus Perceived Risks,* Plenum Press, New York (1983).

V.T. Covello et al. (eds.), *Risk Evaluation and Management,* Plenum Press, New York (1986).

V.T. Covello and M.W. Merkhofer, *Risk Assessment Methods: Approaches for Assessing Health & Environmental Risks,* Plenum Press, New York (1993).

V.T. Covello and J. Mumpower, “Risk Analysis and Risk Management: A Historical Perspective,” in *Risk Evaluation and Management* (V.T. Covello et al., eds.), Plenum Press, New York, pp. 519–540 (1986).

R.E. Donnelly, “Implications of De Minimis Risk Concepts for OSHA,” in *De Minimis Risk* (C. Whipple, ed.), Plenum Press, New York, pp. 95–99 (1987).

R.F. Fahy, “Building Fire Simulation Model. An Overview,” *Fire Safety Journal,* 9, pp. 189–203 (1985).

A. Finkel, “Comparing Risks Thoughtfully,” *Risk: Health, Safety & Environment,* 7, 4, pp. 325–359 (1996).

B. Fischhoff, “Acceptable Risk: A Conceptual Proposal,” *Risk: Health, Safety & Environment,* 5, 1, pp. 1–28 (1994).

B. Fischhoff, “Public Values in Risk Research,” *The Annals of the American Academy of Political and Social Science,* 545, pp. 75–84 (1996).

B. Fischhoff, “Ranking Risks,” *Risk: Health, Safety & Environment,* 6, 3, pp. 191–202 (1996).

B. Fischhoff, P. Slovic, and S. Lichtenstein, “Lay Foibles and Expert Fables in Judgements About Risk,” *The American Statistician,* 36, 3, pp. 240–255 (1982).

R.W. Fitzgerald, “Thoughts on Building Codes, Design Standards, and Performance Evaluations for Fire,” Proceedings of the First International Conference on Performance-Based Codes and Fire Safety Design Methods, SFPE, Bethesda, MD, pp. 127–137 (1997).

H. Frantzich. *Uncertainty and Risk Analysis in Fire Safety Engineering*. PhD thesis, Lund University Sweden, Department of Fire Safety Engineering, 1998.

W. Freudenburg, “Perceived Risk, Real Risk: Social Science and the Art of PRA,” *Science,* 242, pp. 44–49 (1988).

S.O. Funtowicz and J.R. Ravetz, “Three Types of Risk Assessment,” in *Risk Analysis in the Private Sector* (Whipple and Covello, eds.), Plenum Press, New York (1985).

B.J. Garrick and W.C. Gekler (eds.), *The Analysis, Communication and Perception of Risk,* Plenum Press, New York (1991).

T.S. Glickman and M. Gough (eds.), *Readings in Risk,* Resources for the Future, Washington, DC (1990).

J.D. Graham et al. “Science and Analysis: Roles in Risk and Decision Making,” in *Risk Evaluation and Management (*V.T. Covello et al., eds.), Plenum Press, New York, pp. 503–518 (1986).

J.R. Hall, Jr., “Societal Issues in Performance-Based Fire Safety Design,” in *Proceedings of the Workshop on Performance-Based Fire Safety Design, the Society of Fire Protection Engineers and the Centre for Environmental and Risk Engineering,* Victoria University of Technology, Melbourne, Australia (1997).

J.R. Hall, Jr., “Using Data for Public Education Planning and Decision Making,” in *Fire Protection Handbook,* 20th ed. (A.E. Cote et al., eds.), National Fire Protection Association, Quincy, MA, pp. 5-103–5-118 (2008).

J.R. Hall, Jr., and A.E. Cote, “An Overview of the Fire Problem and Fire Protection,” in *Fire Protection Handbook,* 20th ed. (A.E. Cote et al., eds.), National Fire Protection Association, Quincy, MA, pp. 3-3–3-30 (2008).

J. R. Hall Jr. and A. Sekizawa, “Fire risk analysis: General conceptual framework for describing models,” *Fire Technology*, Volume 27, Issue 1, pp 33–53 (1991).

Y. Hasemi, "Wooden 3-Storey Apartment Building Shake and Burn Test Report," Building Research Institute, Tsukuba, Japan (1992).

Health and Safety Executive, *The Tolerability of Risk from Nuclear Power Stations,* HMSO, London (1988).

S. Hostikka and O. Keski-Rahkonen, "Probabilistic Simulation of Fire Scenarios," *Nuclear Engineering and Design*, 224:301–311, 2003.

S. Hostikka, *Development of fire simulation models for radiative heat transfer and probabilistic risk assessment*. PhD thesis, VTT Technical Research Centre of Finland, 2008.

House Committee on Science, *Unlocking Our Future: Toward A New National Science Policy,* Washington, DC (1998).

D.W. Hubbard, *The Failure of Risk Management: Why It's Broken and How to fix It*, John Wiley & Sons Inc., Hoboken, NJ, 2009.

C.R. Jennings, "Socioeconomic Characteristics and Their Relationship to Fire Incidence: A Review of the Literature," *Fire Technology,* 35, 1, pp. 7–34 (1999).

X. Jing and H. Chongfu, "Fire risk analysis of residential buildings based on scenario clusters and its application in fire risk management," *Fire Safety Journal*, Special Issue on Spatial Analytical Approaches in Urban Fire Management, doi:10.1016/j.firesaf.2013.09.022, Volume 62, Part A, Pages 72–78 (2013)

S.N. Jonkman, P.H.A.J.M. van Gelder, and J.K. Vrijling, "An Overview of Quantitative Risk Measures for Loss of Life and Economic Damage," *Journal of Hazardous Materials,* 99, 1, pp. 1–30 (2003).

D. Kahneman and A. Tversky, "The Psychology of Preferences," *Scientific American,* 246, 1, pp. 162–173 (1982).

R.E. Kasperson, "Acceptability of Human Risk," *Environmental Health Perspectives,* 52, pp. 15–20 (1983).

R.E. Kasperson, "Six Propositions for Public Participation and Their Relevance for Risk Communication," *Risk Analysis,* 6, 3, pp. 275–281 (1986).

R.E. Kasperson, "The Social Amplification of Risk: Progress in Developing an Integrative Framework," *Social Theories of Risk* (Krimsky and Golding, eds.), Praeger, Westport, CT, pp. 153–178 (1992).

R. Kasperson, D. Golding, and S. Tuler, "Social Distrust as a Factor in Siting Hazardous Facilities and Communicating Risks," *Journal of Social Issues,* 48, 4, pp. 167–187 (1992).

R.E. Kasperson and J.X. Kasperson, "Determining the Acceptability of Risk: Ethical and Policy Issues," in *Proceedings of Risk: A Symposium on the Assessment and Perception of Risk to Human Health in Canada* (J.T. Rogers and D.V. Bates, eds.), Royal Society of Canada (1982).

R.E. Kasperson and J.X. Kasperson, "Hidden Hazards," in *Acceptable Evidence: Science and Values in Hazard Management* (D.C. Mayo and R. Hollander, eds.), Oxford University Press, New York, pp. 9–28 (1990).

R. Kasperson et al., "The Social Amplification of Risk: A Conceptual Framework," *Risk Analysis,* 8, pp. 177–187 (1988).

R.E. Kasperson et al., *Corporate Management of Health & Safety Hazards: A Comparison of Current Practice,* Westview Press, Boulder, CO (1988a).

R.E. Kasperson and I. Palmlund, "Evaluating Risk Communication," in *Effective Risk Communication* (V.T. Covello et al., eds.), Plenum Press, New York, pp. 143–158 (1989).

R.E. Kasperson and P.J.M. Stallen (eds.), *Communicating Risk to the Public,* Kluwer Academic Publishers, Dordrecht, Netherlands (1991).

R. Kates et al., *Perilous Progress: Managing the Hazards of Technology,* Westview Press, Boulder, CO (1985).

R.L. Keeney, *Value Focused Thinking: A Path to Creative Decision Making,* Harvard University Press, Cambridge, MA (1992).

R.L. Keeney, "The Role of Values in Risk Management," *The Annals of the American Academy of Political and Social Science,* 545, pp. 126–134 (1996).

P.R. Kleindorfer, H.C. Kunreuther, and P.J.H. Schoemaker, *Decision Sciences: An Integrative Perspective,* Cambridge University Press, New York (1993).

M. Kobayashi, "A Methodology for Evaluating Fire/Life Safety Planning of Tall Buildings," in "Evaluation of Fire Safety in Buildings," *Occasional Report of Japanese Association of Fire Science and Engineering* (Nihon Kasaigakka, ed.), 3, pp. 204–214 (1979).

S. Krimsky and D. Golding (eds.), *Social Theories of Risk,* Praeger, Westport, CT (1992).

H. Kunreuther and P. Slovic, "Science, Values, and Risk," in special edition of *The Annals of the American Academy of Political and Social Science* (Kunreuther and Slovic, eds.), 545, pp. 116–125 (1996a).

H. Kunreuther and P. Slovic (eds.), "Challenges in Risk Assessment and Risk Management," in special edition of *The Annals of The American Academy of Political and Social Science,* 545 (1996b).

T.T. Lie, "Safety Factors for Fire Loads," *Canadian Journal of Civil Engineering,* 6, pp. 617–628 (1979).

W-C.T. Ling and R.B. Williamson, "Using Fire Tests for Quantitative Risk Analysis," in *ASTM Special Publication STP 762* (G.T. Castino and T.Z. Harmathy, eds.), American Society for Testing and Materials, Philadelphia (1982).

D. Litai, *A Risk Comparison Methodology for the Assessment of Acceptable Risk,* Ph.D. Dissertation, MIT, Cambridge, MA (1980).

D. Litai, D.D. Lanning, and N. Rasmussen, "The Public Perception of Risk," in *The Analysis of Actual Versus Perceived Risks* (V.T. Covello et al., eds.), Plenum Press, New York, pp. 213–224 (1983).

D.A. Lucht (ed.), *Proceedings of the Conference on Fire Safety Design in the 21st Century,* Worcester, MA (1991).

B.D. McDowell and A.C. Lemer, *Uses of Risk Analysis to Achieve Balanced Safety in Building Design and Operations,* National Academy Press, Washington, DC (1991).

B.J. Meacham, "Risk-Informed Decision-Making in Performance-Based Building and Fire Code Development," in *Proceedings of the NFPRF Fire Risk and*

Hazard Assessment Research Application Symposium, NFPRF, Quincy, MA, pp. 62–77 (1998).

B.J. Meacham, "Concepts of a Performance-Based Building Regulatory System for the United States," *NIST GCR 98-762,* NIST, Gaithersburg, MD (1998b).

B.J. Meacham, "The Evolution of Performance-Based Codes and Fire Safety Design Methods," *NIST GCR 98-763,* NIST, Gaithersburg, MD (1998c).

B.J. Meacham, "Integrating Human Factors Issues into Engineered Fire Safety Design," in *Proceedings of the 1st International Symposium on Human Behavior in Fire,* University of Ulster, Northern Ireland, pp. 47–58 (1998d).

B.J. Meacham, "Incorporating Risk Concepts into Performance-Based Building and Fire Code Development," in *Proceedings of the Second Conference on Fire Design in the 21st Century,* Worcester, MA (1999a).

B.J. Meacham, "Integrating Human Behavior and Response Issues into Fire Safety Management of Facilities," *Facilities,* 17, 9/10, pp. 303–312 (1999b).

B.J. Meacham, "Integrating Human Factors Issues into Engineered Fire Safety Design," *Fire and Materials,* 23, pp. 273–279 (1999c).

B.J. Meacham, "Challenges in Decision-Making for Fire Risk Problems," *Journal of Fire Protection Engineering,* 14, 2, pp. 149–168 (2004).

B.J. Meacham and M. Johann (eds.), *Extreme Event Mitigation in Buildings: Analysis and Design,* National Fire Protection Association, Quincy, MA (Apr. 2006).

B.J. Meacham, "Using Risk as a Basis for Establishing Tolerable Performance: An Approach for Performance-Based Building Regulation," in *Proceedings of the 7th International Conference on Performance-Based Codes and Fire Safety Design Methods,* Society of Fire Protection Engineers, Bethesda, MD (Apr. 2008).

B.J. Meacham and C. Galioto, "Protecting Against Extreme Events," in *Fire Protection Handbook,* 20th ed. (A.E. Cote et al., eds.), National Fire Protection Association, Quincy, MA, pp. 1-109–1-136 (2008).

M. Modarres and F. Joglar-Billoch, "Reliability," in *SFPE Handbook of Fire Protection Engineering,* 3rd ed. (P.J. DiNenno et al., eds.), National Fire Protection Association, Quincy, MA, pp. 5-24–5-39 (2002).

M.G. Morgan, "Choosing and Managing Technology-Induced Risk," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 17–28 (1990).

NFPA, *Fire Protection Handbook,* 20th ed., Quincy, MA (2008).

NFPA 101A, *Guide on Alternative Approaches to Life Safety,* National Fire Protection Association, Quincy, MA (2007).

NIST "1994 Northridge Earthquake: Performance of Structures, Lifelines and Fire Protection Systems," *NIST Special Publication 862* (ICSSC TR14), NIST, Gaithersburg, MD (1994).

NKB "Performance Requirements for Fire Safety and Technical Guide for Verification by Calculation," *NKB Committee and Work Reports, 1994:07 E,* Nordic Committee on Building Regulations (NKB), Fire Safety Committee, Helsinki, Finland (1995).

K.A. Notarianni and P. Fischbeck, "A Methodology for the Quantitative Treatment of Variability and Uncertainty in Performance-Based Engineering Analysis and/or Decision Analysis with a Case Study in Residential Fire Sprinklers," in *Proceedings of the Second International Conference on Performance-Based Codes and Fire Safety Design Methods,* ICBO and SFPE, Whittier, CA, pp. 297–311 (1998).

NRC *Risk Assessment in the Federal Government: Managing the Process,* National Research Council, National Academy Press, Washington, DC (1983).

NRC *Improving Risk Communication,* (J.F. Ahearne et al., eds.), National Research Council, National Academy Press, Washington, DC (1989).

NRC *Science and Judgment in Risk Assessment,* National Academy Press, Washington, DC (1994).

T. O'Riordan, "Approaches to Regulation," in *Regulating Industrial Risks—Science, Hazards and Public Protection* (H. Otway and M. Peltu, eds.), Butterworths, London, pp. 20–39 (1985).

H. Otway "Regulation and Risk Analysis," in *Regulating Industrial Risks—Science, Hazards and Public Protection* (H. Otway and M. Peltu, eds.), Butterworths, London, pp. 1–19 (1985).

H. Otway and M. Peltu (eds.), *Regulating Industrial Risks—Science, Hazards and Public Protection,* Butterworths, London (1985).

H. Otway and D. Von Winterfeldt, "Beyond Acceptable Risk: On Social Acceptability of Technologies," *Policy Sciences,* 14, pp. 247–256 (1982).

H. Otway and B. Wynne, "Risk Communication: Paradigm and Paradox," *Risk Analysis,* 9, 2, pp. 141–145 (1989).

M.E. Pate, "Acceptable Decision Processes and Acceptable Risks in Public Sector Regulations," *IEEE Transactions on Systems, Man, and Cybernetics,* SMC-13, 3, pp. 113–124 (1983).

C. Perrow, *Normal Accidents,* Basic Books, New York (1984).

N. Pidgeon et al., "Risk Perception," *Risk: Analysis, Perception and Management,* Report of the Royal Society, London, pp. 89–134 (1992).

A. Plough and S. Krimsky, "The Emergence of Risk Communication Studies: Social and Political Context," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 223–232 (1990).

M. Pollak, "Public Participation," in *Regulating Industrial Risks—Science, Hazards and Public Protection* (H. Otway and M. Peltu, eds.), Butterworths, London, pp. 76–93 (1985).

R.A. Pollak, "Government Risk Regulation," *The Annals of the American Academy of Political and Social Science,* 545, pp. 25–34 (1996).

D. Proske, *Catalogue of Risks: Natural, Technical, Social and Health Risks*, Springer Berlin Heidelberg, ISBN 978-3540795544, 2008

D.J. Rasbash, "Criteria for Acceptability for Use with Quantitative Approaches to Fire Safety," *Fire Safety Journal,* 8, pp. 141–158 (1984).

N.C. Rassmussen, *Reactor Safety Study: WASH-1400,* U.S. Nuclear Regulatory Commission, Washington, DC (1975).

O. Renn, "Concepts of Risk: A Classification," in *Social Theories of Risk* (Krimsky and Golding, eds.), Praeger, Westport, CT, pp. 54–79 (1992).

O. Renn and D. Levine, "Credibility and Trust in Risk Communication," in *Communicating Risks to the Public* (R.E. Kasperson and P.M. Stallon, eds.), Kluwer, Dordrecht, Netherlands, pp. 175–218 (1991).

W.D. Rowe, *Anatomy of Risk,* John Wiley and Sons, New York (1977).

W.D. Rowe, "Understanding Uncertainty," *Risk Analysis,* 14, 5, pp. 743–750 (1994).

A. Sekizawa, "Fire Risk Analysis: Its Validity And Potential For Application In Fire Safety," *Fire Safety Science,* 8: 85–100. doi:10.3801/IAFSS.FSS.8-85 (2005).

SFPE *Proceedings of the 1998 International Conference on Performance-Based Codes and Fire Safety Design Methods,* SFPE and ICBO, Bethesda, MD (1998).

T.J. Shields, *A Fire Safety Evaluation Points Scheme for Dwellings,* Ph.D. Dissertation, University of Ulster, Jordanstown, Northern Ireland (1990).

T.J. Shields (ed.), *Proceedings of the 1st International Symposium on Human Behaviour in Fire,* University of Ulster, Antrim, Northern Ireland (1998).

N. Siu and G. Apostolakis, "Uncertain Data and Expert Opinions in the Assessment of the Unavailability of Fire Suppression Systems," *Fire Technology,* 24, pp. 138–162 (1988).

P. Slovic, "Perception of Risk: Reflections on the Psychometric Paradigm," in *Social Theories of Risk* (Krimsky and Golding, eds.), Praeger, Westport, CT (1992).

M.B. Spangler, "A Summary Perspective on NRC's Implicit and Explicit Use of De Minimis Risk Concepts in Regulating for Radiological Protection in the Nuclear Fuel Cycle," in *DeMinimis Risk* (C. Whipple, ed.), Plenum Press, New York, pp. 111–143 (1988).

C. Starr, "Societal Benefit vs. Technological Risk," *Science,* 165, pp. 1232–1238 (1969).

C. Starr, "Risk Management, Assessment, and Acceptability," in *Uncertainty in Risk Assessment, Risk Management, and Decision Making* (V.T. Covello et al., eds.), Plenum Press, New York, pp. 63–70 (1986).

T. Tanaka, D. Nii, J. Yamaguchi, H. Notake, and Y. Ikehata, "A Study on Risk-Based Evacuation Safety Design Method in Fire for Office Buildings," *Proceedings, Interflam 9*, Interscience Communications, Ltd, UK, p. 849–860, 2010.

T. Tanaka, "Risk-Based Selection of Design Fires to Ensure an Acceptable Level of Evacuation Safety." *Fire Safety Science – Proceedings of the Ninth International Symposium*, IAFSS, pp 49–62, 2008.

I.R. Thomas, I.D. Bennetts, P. Dayawansa, D.J. Proe, and R.R. Lewis, *Fire Tests of the 140 William Street Office Building*, Report No. BHPR/ENG/R/92/043/SG2C, BHP Research—Melbourne Laboratories, Australia, Feb. 1992.

W.K. Viscusi, *Regulating Consumer Product Safety,* American Enterprise Institute for Public Policy, Washington, DC (1984).

Warren Centre "Project Report" and "Technical Papers, Books 1 and 2," Fire Safety and Engineering Project, The Warren Centre for Advanced Engineering, the University of Sydney, Australia (1989).

J.M. Watts, Jr., "Dealing with Uncertainty: Some Applications in Fire Protection Engineering," *Fire Safety Journal,* 11, pp. 127–134 (1986).

C. Whipple (ed.), *De Minimis Risk,* Plenum Press, New York (1987).

C.A. Williams and R.M. Heins, *Risk Management and Insurance,* 4th ed., McGraw-Hill, New York (1981).

R. Wilson, "Analyzing the Daily Risks of Life," in *Readings in Risk* (Glickman and Gough, eds.), Resources for the Future, Washington, DC, pp. 55–61 (1990).

A. Wolski, *Addressing Building Fire Safety as an Acceptable Risk Problem: A Guide for Developing Performance-Based Fire Safety Regulations,* Masters Thesis, Worcester Polytechnic Institute, Worcester, MA (1999).

A. Wolski, N. Dembsey, and B. Meacham, "Application of Acceptable Risk Principles to Performance-Based Building and Fire Safety Code Development," in *Proceedings of the 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods,* ICBO and SFPE, Whittier, CA (1998).

A. Wolski, N. Dembsey, and B. Meacham, "Accommodating Perceptions of Risk in Performance-Based Building Fire Safety Code Development," *Fire Safety Journal,* 34, 3, pp. 297–310 (2000).

B. Wynne, "Risk and Social Learning: Reification to Engagement," in *Social Theories of Risk* (Krimsky and Golding, eds.), Praeger, Westport, CT, pp. 275–300 (1992).

D. Yung and G.V. Hadjisophocleous, "The Use of the NRCC Risk-Cost Assessment Model to Apply for Code Changes for 3-Storey Apartment Buildings in Australia," in *Proceedings of the Symposium on Computer Applications in Fire Protection Engineering,* Worcester, MA, pp. 57–62 (1993).

R.J. Zeckhauser and W.K. Viscusi, "The Risk Management Dilemma," in special edition of *The Annals of the American Academy of Political and Social Science* (Kunreuther and Slovic, eds.), 545, pp. 144–154 (1996).

Brian J. Meacham is an Associate Professor at Worcester Polytechnic Institute (WPI) in the United States. He has more than 30 years of professional experience as a consultant, researcher and educator in the areas of risk-informed and performance-based fire engineering and regulation. He is a licensed Professional Engineer (US), a Chartered Engineer (U.K.), a Fellow of the Society of

Fire Protection Engineers, and a Fellow of the Institution of Fire Engineers.

David Charters is with the specialist risk management consulting and training company Risktec Solutions in the U.K. He has more than 25 years of professional experience as a consultant, research and educator in fire risk analysis and engineering. He is a Chartered Engineer (U.K.), a Professional Member of the Society of Fire Protection Engineers, and a Fellow of the Institution of Fire Engineers.

Peter Johnson is a Principal and Fellow with the global engineering consultancy and design firm Arup and is based in Melbourne, Australia. He has had 40 years of professional fire engineering experience involving fire testing, education, and design of buildings and transport infrastructure. He is an Arup Fellow and a Fellow of the Society of Fire Protection Engineers.

Matthew Salisbury is a practicing Fire Engineer with Michael Slattery Associates. He has 15 years of fire engineering experience, is a Chartered Engineer (U.K.), a Member of the Society of Fire Protection Engineers and a Member of the Institution of Fire Engineers. He has developed a number of fire engineering software packages, including BuildingQRA.