Risk-Informed, Performance-Based Industrial Fire Protection
An Alternative to Prescriptive Codes
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Chapter 1
Program Objectives

Chapter Contents

PROGRAM OBJECTIVES 1

1.1 INTRODUCTION

Risk-informed, performance-based fire protection is an integration of decision analysis and quantitative risk assessment with a defined approach for quantifying the performance success of fire protection systems (FPS).

Risk-informed involves the use of quantitative risk assessment (QRA) evaluation tools and techniques (e.g., event trees, fault trees) in conjunction with traditional fire protection engineering methods and deterministic fire modeling tools. This quantitative information provides input for making informed decisions regarding fire and explosion risk impacts and cost-effective strategies for risk reduction.

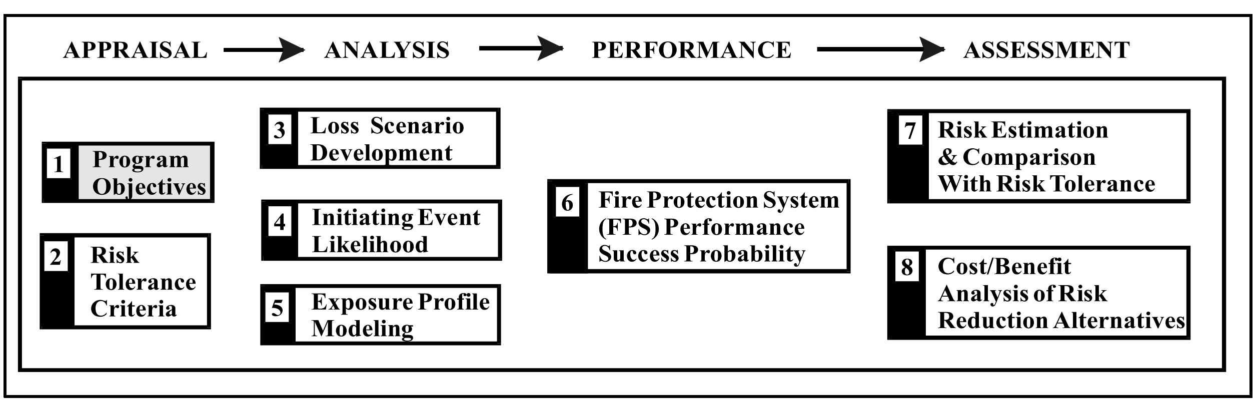
Performance-based fire protection is a quantitative, probabilistic measure of fire protection success based on functional performance requirements derived from specific scenario and risk tolerance criteria. Performance is evaluated within an event tree risk model on a conditional probability basis that is equated by three primary factors:

- Response effectiveness
- Online availability
- Operational reliability

The process of evaluating risk and performance under a variety of scenarios requires eight steps, which form the basis for the chapters of this book (Fig. 1.1). This chapter addresses program objectives (Step 1 in the risk-informed, performance-based decision making process). The benefits of risk-based decision making are addressed in Sect. 1.2. Risk-informed methodology and steps are summarized in Sect. 1.3. Sect. 1.4 discusses project management issues and Sect. 1.5 discusses risk communications.

Risk-informed programs assist management decision makers by providing a structured, consistent method to quantify risk, evaluate risk reduction alternatives, and perform cost/benefit analysis. As a starting point the decision makers must understand the concept of risk, risk-based program motivation, risk methodology, and project management issues.

Fig. 1.1: Risk-Informed, Performance-Based Fire Protection Steps



1.1.1 Risk Defined

In risk-based decision making, RISK is understood in terms of the likelihood and consequences of incidents that could expose people, property, and the environment to the harmful effects of fire or explosion hazards. Likelihood is determined in terms of either frequency (how often can this happen) or probability (what are the chances this will happen).

RISK = Likelihood of an Event (F) x Expected Consequences (C)

Fire and explosion risk analysis is very scenario (Sn) specific. The risk associated with multiple initiating event scenarios is the sum of the scenarios:

$$\text{RISK} = \Sigma_{Sn} \, F \times C$$

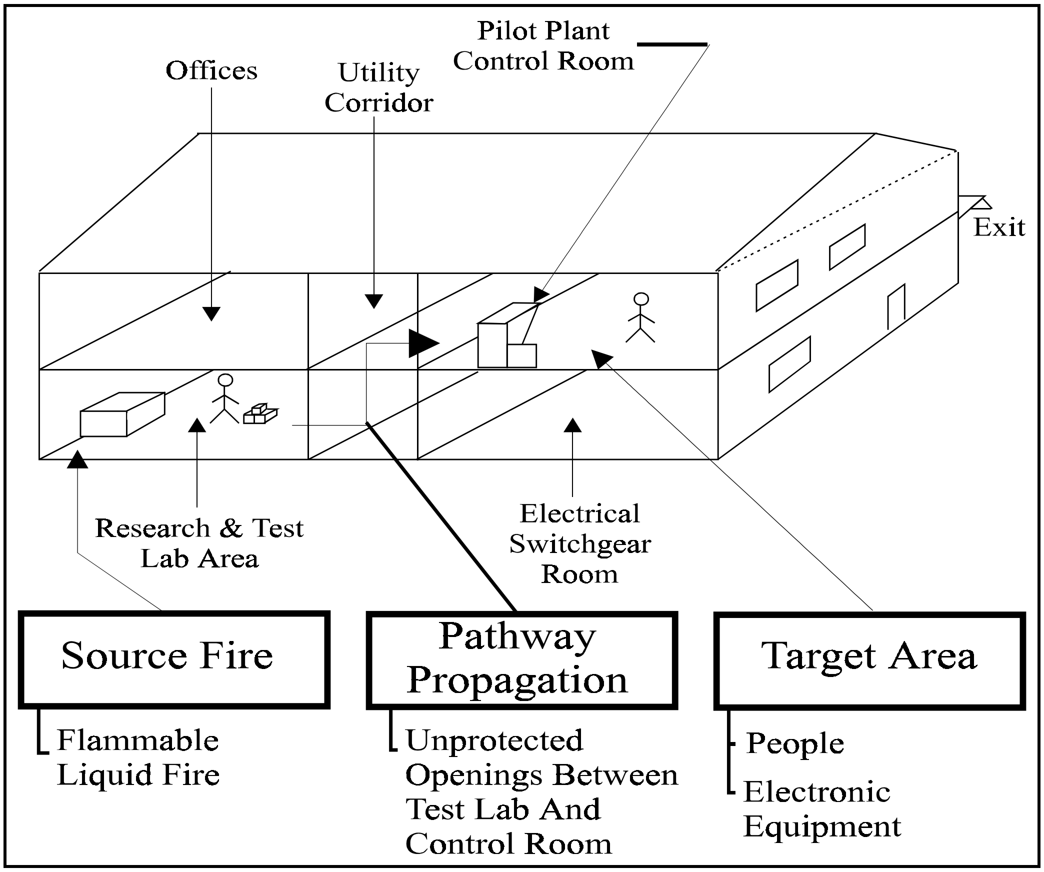
The concept of RISK is sometimes difficult to grasp at first as many people use hazard related terms and risk terms interchangeably without regard to the differences between definitions. Table 1.1 provides some basic definitions.

Table 1.1: Some Definitions

TERM	DEFINITION	KEY WORDS
Hazard	Hazard is a chemical or physical condition that has the potential for causing damage to people, property, or the environment. An example would be flammable liquids or explosive gases or dusts used in process or in storage	"Potential for harm"
Severity	Severity is a qualitative or quantitative estimate of the hazard intensity in terms of source intensity, time, and distance; for example heat flux, temperature, toxic or corrosive smoke concentrations, explosion over-pressure versus distance	"Intensity versus time and distance"
Consequences	Consequences are expected effects from the realization of the hazard and severity, usually measured in terms of property damage, business interruption, life safety exposure, environmental impact, company image, etc.	"Expected damage effects"
Risk	Risk is a quantitative measure of fire or explosion incident loss potential in terms of both the event likelihood and aggregate consequences	"Likelihood and consequences"

Figure 1.2 presents an example pilot plant building, which can be used to further illustrate the difference between hazard and risk related terms.

Fig. 1.2: Example Pilot Plant



Concerning Fig. 1.2:

Hazard: The hazard is the flammable liquid in the Lab Area and potential for a flammable liquid fire (i.e., potential for harm).

Severity: The severity would be the potential fire hazard intensity versus time as seen by the target, which is the Pilot Plant Control Room. The intensity could be measured in terms of heat flux, temperatures, corrosive and toxic smoke concentrations versus time (i.e., intensity versus time and distance).

Consequences: The consequences relate the potential expected damage to property (i.e., equipment, structure), people (i.e., operators who must remain in the control room), business interruption, company image, etc. For example, assume the target area includes the following values:

Property Damage and Business Interruption:	$17 million
Operator Value (Life Safety Exposure):	$ 3 million

If the combined consequences were measured in monetary terms and estimated at 100% loss potential, then for this example, the consequence would be $20 million.

Risk: The risk measure involves an estimation of the potential likelihood of having a flammable liquid fire in the Lab Area and the consequences.

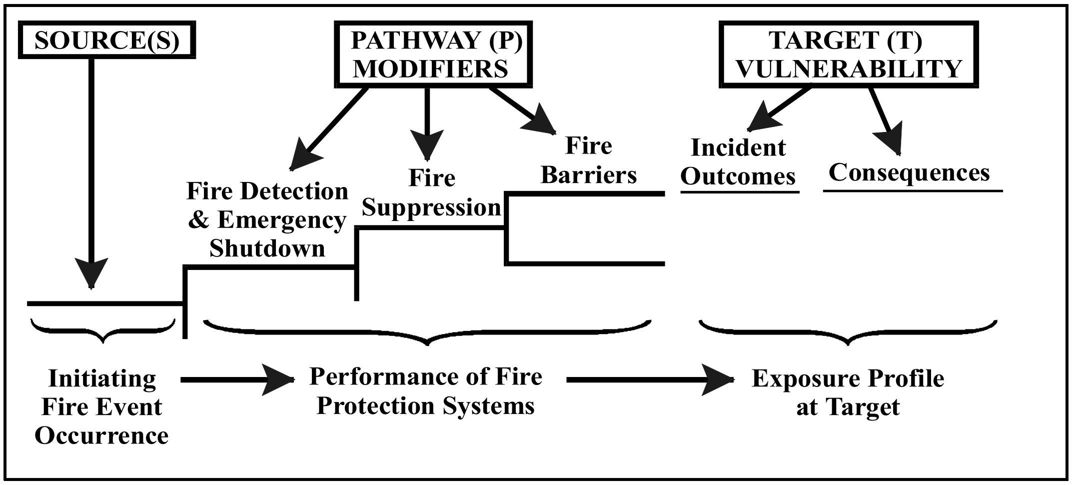
For example, if the fire event likelihood was estimated at 0.02 fire events/year (approximately 1 fire every 50 years) and 100% consequences ($20 million), then the risk would be:

RISK = Likelihood x Consequences
RISK = 0.02 fire events/year x $20 million loss/per event
Annualized Risk = $400,000.00

Unmitigated Risk Versus Mitigated Risk

The risk equation used above is for unmitigated risk. It does not consider the performance of loss control measures such as fire protection systems. Mitigated risk considers the probability of fire protection system (FPS) performance success. FPS performance is introduced into the risk equation with the use of event tree analysis (ETA). ETA is discussed in detail in Chaps. 3, 5, 7, and 8; the point here is to introduce how FPS performance is integrated into the risk equation. Figure 1.3 provides a graphical presentation of the relationship between Source ÷ Pathway ÷ Target scenario development and the event tree risk model structure.

Fig. 1.3: Relationship Among Source ÷ Pathway ÷ Target to Event Tree Analysis



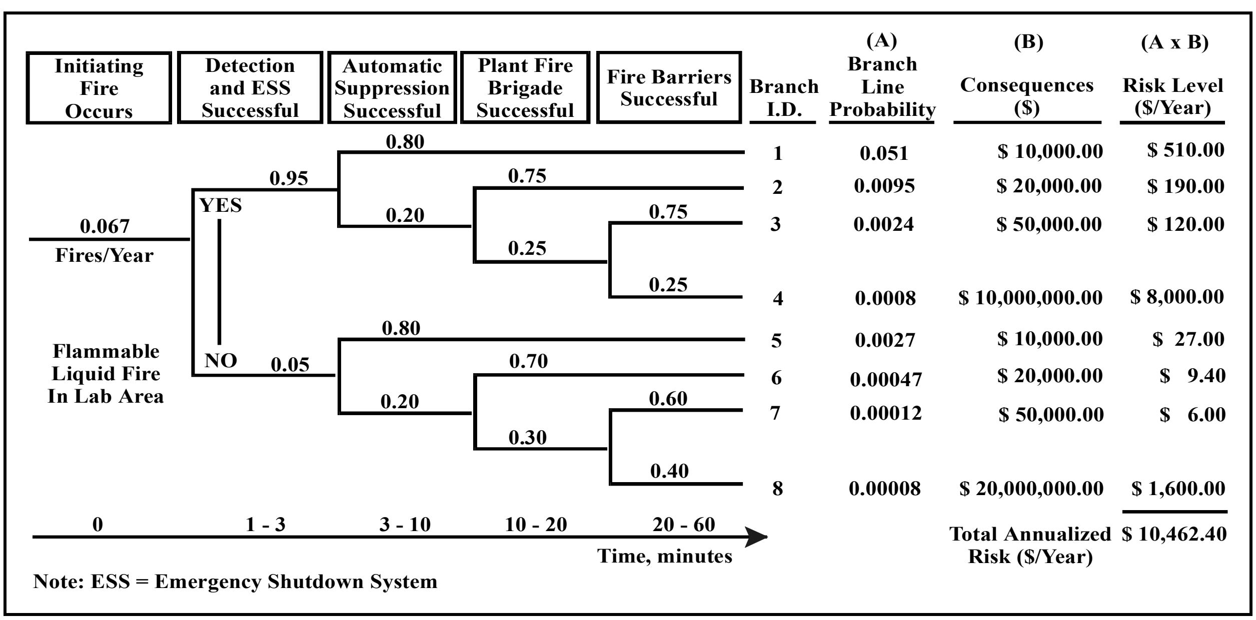
Based on Fig. 1.3, the RISK equation for defined scenarios becomes:

$$\text{RISK} = \begin{matrix}\text{Initiating}\\ \text{Fire Event}\\ \text{Likelihood}\\ (F)\end{matrix} \times \begin{matrix}\text{FPS}\\ \text{Performance Success}\\ \text{Probability}\\ (P_{FPS})\end{matrix} \times \begin{matrix}\text{Consequences}\\ (C)\end{matrix}$$

$$Risk = \sum_{Sn} F \, x P_{FPS} x \ C$$

Figure 1.4 provides an example of an event tree structure that could be used for evaluation of the Pilot Plant Building in Fig. 1.2.

Fig. 1.4: Example Event Tree Structure for Fig. 1.2



The example event tree in Fig. 1.4 includes the performance success probability of the following fire protection measures:

- Detection and emergency shutdown system (ESS) (i.e., shutdown of flammable liquid equipment)
- Automatic suppression (in the room of fire origin)
- Plant fire brigade response
- Fire barrier integrity between the lab and control room

The mitigated total annualized risk for this example is a little over $10,000, which is a significant difference to the previous unmitigated annualized risk estimate of $400,000.

The intent of this discussion was to provide a brief introduction to some concepts and definitions with a focus on the differences between the terms *hazard, consequences, unmitigated risk,* and *mitigated risk estimates*. These concepts are explained in detail throughout this book. The concept of Source ÷ Pathway ÷ Target scenario development and event tree structuring is discussed in more detail in Chap. 3. The development of event likelihood estimates, consequence levels, and FPS performance success probabilities are addressed in Chaps. 4, 5, and 6. Risk estimation and presentation are described in Chap. 7, and cost/benefit analysis of risk reduction alternatives is described in Chap. 8.

1.2 RISK-BASED DECISION MAKING

Risk-based programs can assist decision makers by providing a structured, consistent method to quantify risk and risk reduction alternatives. Quantitative risk-based approaches provide many advantages. The following quote is extracted from reference [1] (underline added for emphasis).

> *"Quantitative risk analysis uses measured or estimated probabilities and consequences. Although we concede that moving from qualitative to quantitative risk analysis multiplies the cost, it exponentially increases the benefit. In addition to the benefits that risk-based methods provide at the qualitative level, quantitative methods calculate expected values for probability and consequence. If the consequence is measured in monetary terms, then the analyst can calculate a probable net present value (NPV) difference between existing conditions and for any proposed change. In all calculations the analyst will naturally develop expected values and "spread" for all of the important parameters. In other words, fully <u>quantitative risk-based methods bridge the gap between engineering and finance. This is because expected value, defined by probability times consequence, is a term that is already used in the financial community</u>."*

Decision making factors or decision characteristics that promote the use of a formal, structured, risk-based approach include the following:

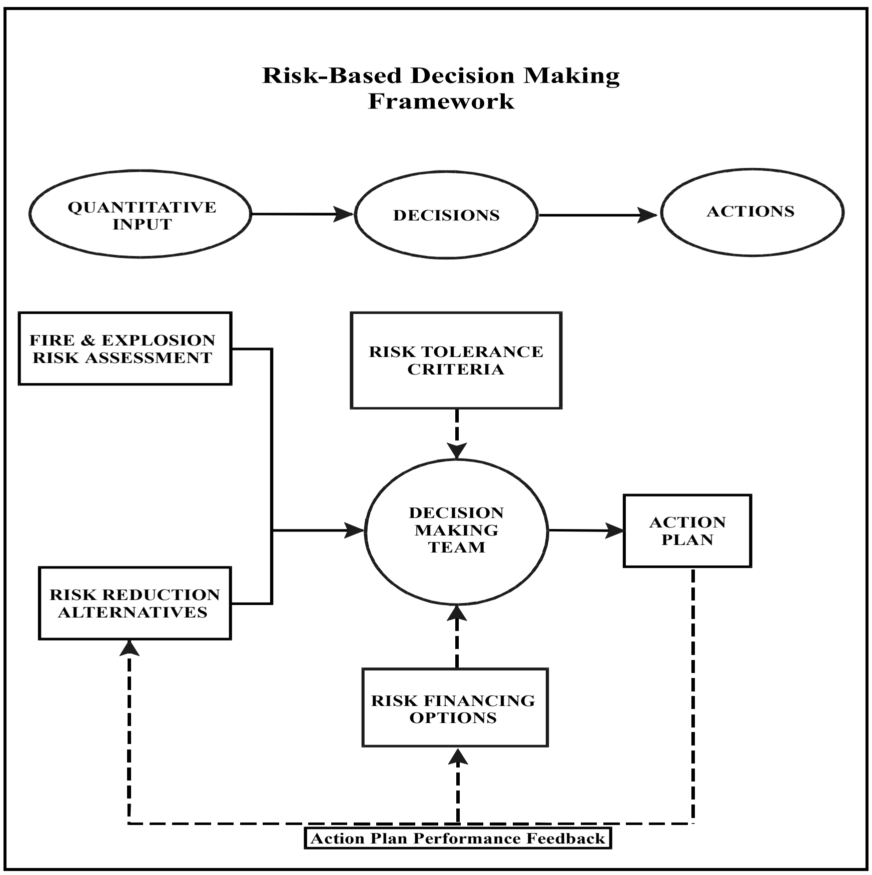
- Decisions involve significant financial impacts.
- Decision maker has many alternatives, both technical and financial, from which to choose.

- Decisions affect other company wide or corporate wide facilities and operations.
- Decisions involve uncertain consequences with multiple dimensions of value.

The risk-based decision making framework generally consists of six decision support modules, as illustrated in Fig. 1.5:

- Fire and explosion quantitative risk assessment (QRA) input
- Risk reduction alternatives
- Risk tolerance criteria
- Risk financing options
- Action plans
- Action plan performance feedback

Fig. 1.5: General Risk-Based Decision Making Framework



At the center of this framework is the decision making team whose members must reach a decision by consensus. Decisions reached by any method other than management consensus may result in lack of commitment and support.

Consensus means the majority of the team accepts and supports the decision. Consensus requires an understanding of the risk-based decision making process, the objectives, methodology, uncertainties, and all possible alternatives. Once understanding is gained, the team can proceed with the process of arriving at decision consensus.

General benefits of risk-informed, performance-based decision making as applied to fire and explosion exposure include:

- Ability to support the cost-effective solution of complex fire and explosion problems
- Ability to evaluate several different risk reduction strategies objectively
- Greatly facilitated communication among managers
- Increased management control over risk reduction strategies and expenditures
- More consistent and objective decisions than those made intuitively and subjectively
- Ability to assist in establishing the optimum balance between fire prevention, protection, and emergency response based on cost/benefit analysis

Risk-based analysis and decision making is widely used by many agencies of the U.S. government, the chemical process industry, the telecommunications industry, the aviation industry, the nuclear industry, and others. The application of fire and explosion risk and performance-based decision analysis will certainly continue to gain widespread acceptance in the future as an alternative to prescriptive building and fire codes.

1.3 METHODOLOGY AND STEPS

Risk-informed, performance-based fire protection is a risk-based decision making methodology and therefore must follow a decision analysis and risk assessment framework. There are numerous books and articles on decision analysis that generally convey the steps presented in Fig. 1.6.

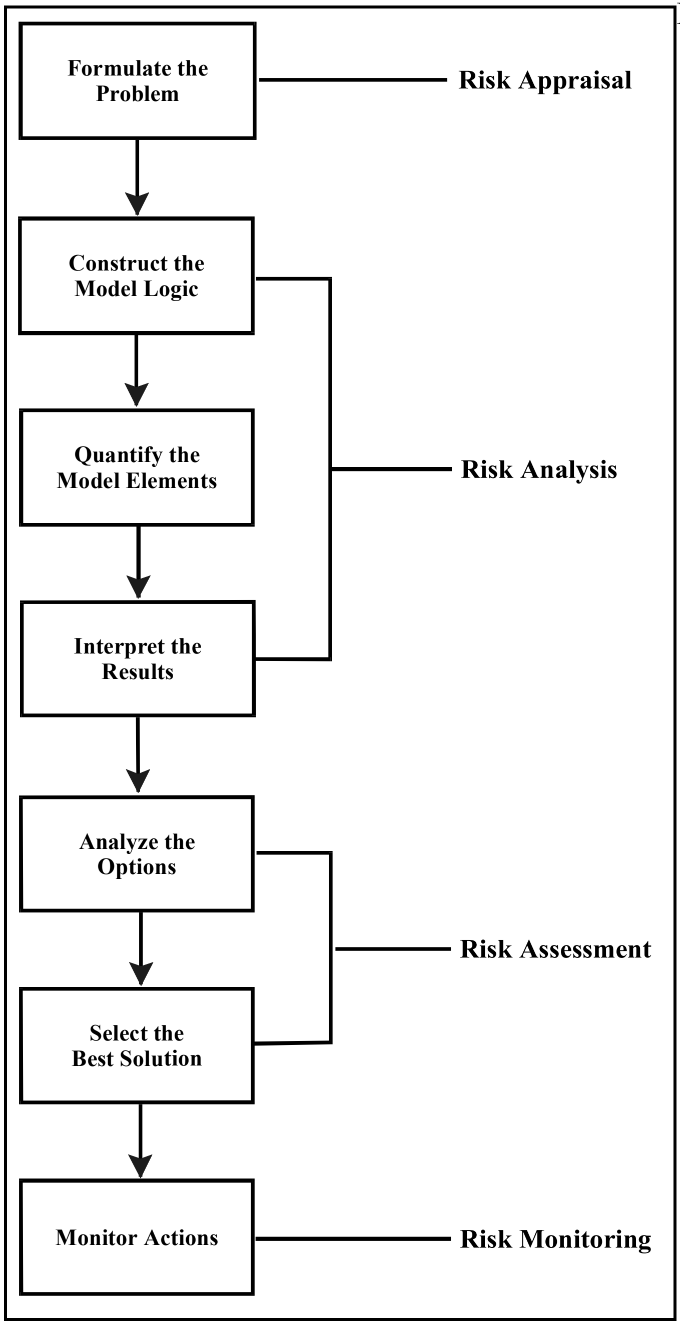


Fig. 1.6: General Decision Analysis Steps

Risk-informed, performance-based decision analysis involves decomposition of the elements of fire and explosion risk and FPS performance to allow detailed study of those elements. This approach forces the risk assessment team to break down the problem in a structured, consistent "step-approach" manner.

The steps described in this book are patterned after the QRA steps developed by the Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers (AIChE), and described in their book, *Guidelines for Chemical Process Quantitative Risk Analysis*.[2] This approach has been accepted and adopted by U.S. chemical, oil, and gas industries performing QRA projects and is now being used in numerous other applications. These steps are presented in Fig. 1.7 and consist of the following:

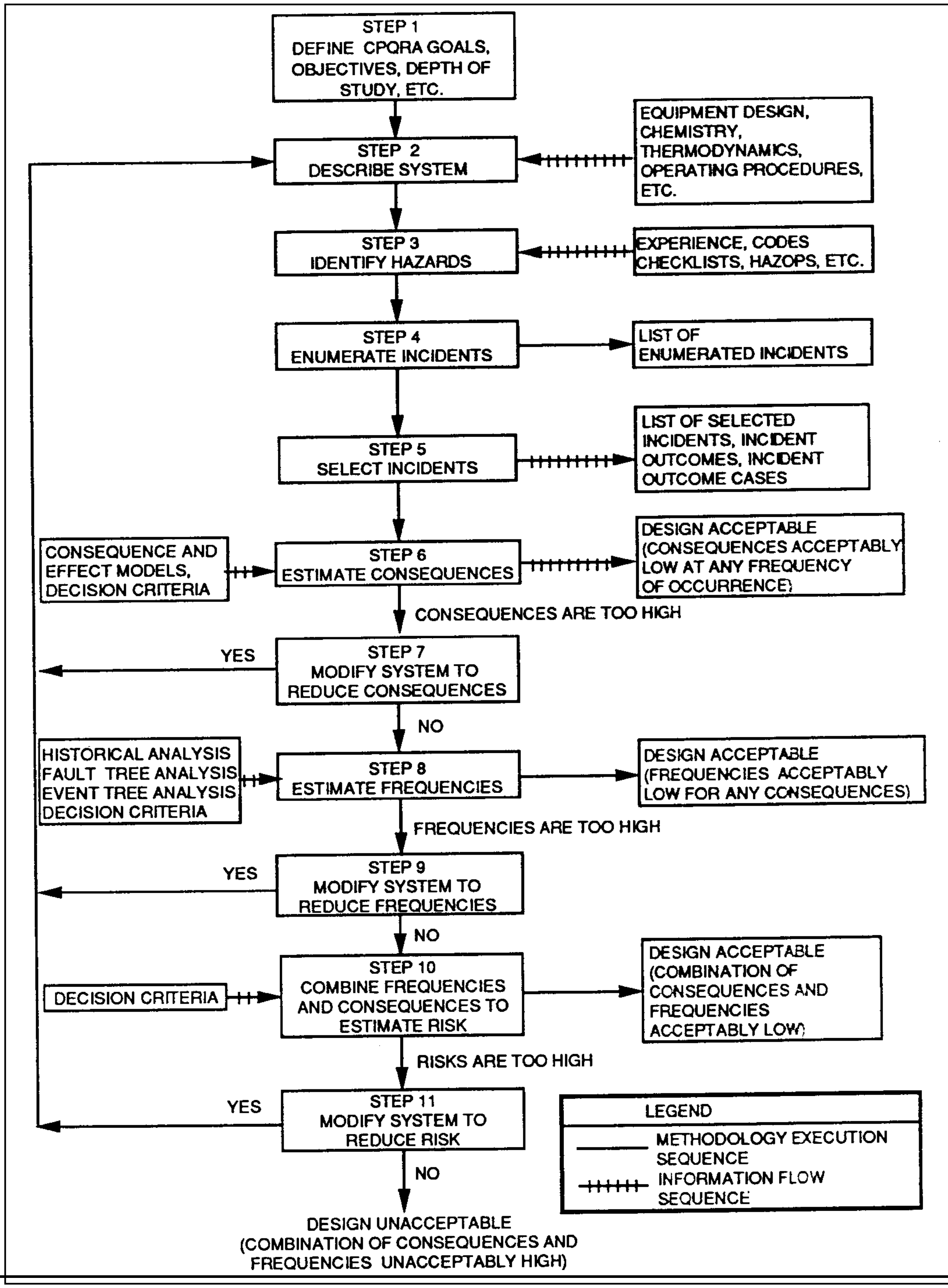
- *Formulation*: Define goals, establish scope, describe system and assemble background information.
- *Hazard Identification*: Identify hazards and potential incidents and select those to be considered in the study.
- *Consequence Estimation*: Estimate consequences of incidents considered in the study, including both the physical effects and the impact of those physical effects on people, property, and environment.
- *Likelihood Estimation*: Estimate the likelihood of the incidents considered in the study.
- *Risk Estimation*: Combine the estimates of consequences and likelihood into appropriate measures of risk.
- *Risk Modification*: If the risks are too high, modify the system to reduce the risk

Risk-informed, performance-based fire protection is an integration of decision analysis and QRA with a defined step for quantifying FPS performance success. The steps in Fig. 1.6 (Decision Analysis) and Fig. 1.7 (Chemical Process Quantitative Risk Analysis) can be grouped under the following headings:

- Risk Appraisal
- Risk Analysis
- Risk Assessment

This grouping, along with the addition of FPS performance, forms the framework for the risk-informed, performance-based fire protection steps as described in this book.

Fig. 1.7: Chemical Process Quantitative Risk Analysis (CPQRA) Steps



American Institute of Chemical Engineers (AIChE). Center for Chemical Process Safety (CCPS), Guidelines for Chemical Process Quantitative Risk Analysis, New York, NY, 1989.

1.3.1 Risk-Informed, Performance-Based Fire Protection Steps

Figure 1.8 presents the risk-informed, performance-based fire protection steps described in this book. The figure is followed by a short summary of each step:

APPRAISAL
1. Program Objectives
2. Risk Tolerance Criteria

ANALYSIS

3. Loss Scenario Development
4. Initiating Event Likelihood
5. Exposure Profile Modeling

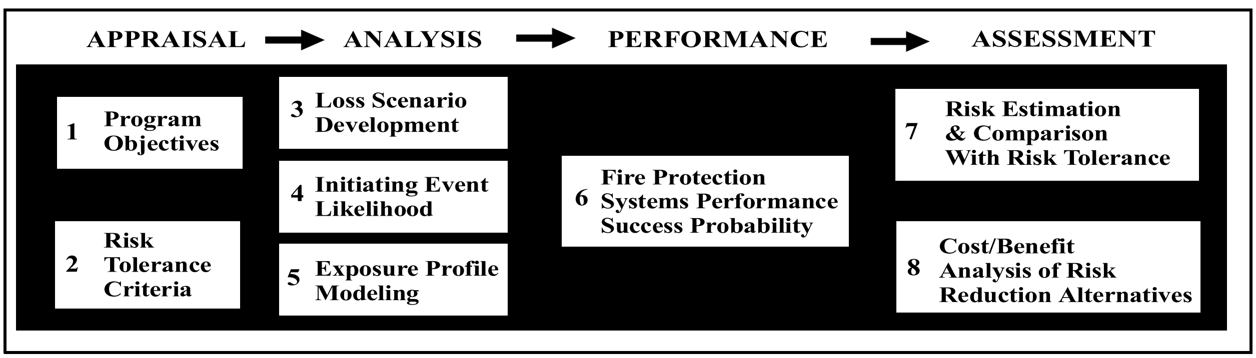
PERFORMANCE

6. FPS Performance Success Probability

ASSESSMENT

7. Risk Estimation and Comparison With Risk Tolerance
8. Cost/Benefit Analysis of Risk Reduction Alternatives

Fig. 1.8: Risk-Informed, Performance-Based Fire Protection Steps



1. Program Objectives

Risk-informed, performance-based program objectives involve:

- Establishing a risk-based decision making framework and team concept
- Applying a structured, consistent methodology to quantify risk and perform risk reduction cost/benefit analysis
- Implementing an effective project management plan

2. Risk Tolerance Criteria

Risk tolerance criteria provides a quantitative basis against which risk analysis results and risk reduction efforts are measured. This step provides the methodology for establishing fire and explosion risk tolerance criteria and graphical presentation.

The risk tolerance criteria development process involves the following:

- Must be specific to the defined risk assessment project boundaries
- Must establish measurable quantitative guide values for risk comparison
- Must provide input for evaluating FPS performance success

Risk tolerance criteria is a dynamic measure related to a company's changing business objectives and focus and can be expressed in a variety of ways. In Chap. 2, the following two methods are addressed with examples:

- Total annualized financial impact risk tolerance
- Likelihood of exceeding a defined exposure level

3. Loss Scenario Development

A loss scenario represents the sequence of events that can result in undesirable fire or explosion incidents and consequences. The scenario development process must be:

- Sequentially structured in a time-related manner
- Credible in terms of realistic incident outcomes
- Contain sufficient information to allow the risk analysis team the ability to quantify the scenario

Comprehensive scenario analysis is one of the most important aspects of conducting credible risk-informed, performance-based projects. A comprehensive approach involves:

- Applying a consistent framework and systematic methodology
- Identifying contributing factors associated with fire and explosion initiating events
- Evaluating the exposure versus time profile following the initiating event. Exposure elements include fire growth, propagation, incident outcomes, and potential consequence levels

Step 3 introduces the development of a scenario-based framework with the focus being event tree analysis (ETA) using the concept of Source ÷ Pathway ÷ Target. ETA conveys initiating events, FPS performance, incident outcomes, and consequences. Chapter 3 provides examples of scenario development and event tree structuring.

4. Initiating Event Likelihood

The term "likelihood" is defined as a measure of the expected frequency or probability of a defined initiating fire or explosion event. The modeling methods in Step 4 used to quantify the initiating event likelihoods include the use of:

- Historical data where there is experience from past fire loss incidents (i.e., plant specific data) or from similar systems (i.e., industry specific or generic databases)
- Modeling techniques such as fault tree analysis (FTA), which is used to estimate the likelihood of events where historical data is limited or is inadequate to accurately estimate the likelihood of the fire events of concern
- Engineering judgment that quantifies an expert's state of knowledge or perceptions of the likelihood of potential fire or explosion incidents. This knowledge may be based on historical data, insights gained from previous hazard or risk analysis projects, experience, plant specific information, or a combination of these factors

FTA provides a structured method to quantify initiating fire occurrence events. The benefit of FTA is that it provides a decomposition of the top initiating event into factors that contribute to failure and ignition potentials. The frequencies and probabilities used in the FTA can include a combination of equipment and human failure rate data, plant specific data, probabilities supported by deterministic modeling, and subjective, expert opinion probabilities.

Failure data sources, examples, methods for modifying data using performance integrity measures (PIMs) are described in Chap. 4. An entire section is devoted to ignition probability modeling.

5. Exposure Profile Modeling

An exposure profile is a scenario-specific, graphical representation of what the risk target is subject to in terms of source intensity (e.g., heat, temperature, smoke, toxic, or corrosive gas concentrations, explosion overpressures, etc.) versus time. The modeling approach in Step 5 involves the following:

- Determine the risk target value and vulnerability. Vulnerability is defined in terms of threshold damage limits (TDLs). TDLs are potential failure limits of the target subsystems (e.g., equipment, operators, structure) when exposed to fire or explosion impacts.
- Characterize the source fire heat release rate (HRR). Developing and quantifying the initiating source HRR in a credible manner is a key consideration in the initial development of the exposure profile. The HRR is used to estimate flame height, radiant heat flux, and fire plume size and intensity, all of which affect the exposure at the target.
- Model the event tree scenario fire or explosion incident outcome. Pool fires, torch fires, unconfined spill fires, flash fires, boiling liquid expanding vapor explosion (BLEVE) fireballs, solid materials, and storage configurations can be modeled to evaluate radiant heat flux, temperatures, and smoke concentration intensities at the target. Unconfined vapor cloud explosions and confined explosions can be modeled to evaluate potential explosion overpressures at the target.
- Develop FPS response parameters. Based on the exposure profile, response times for detection systems, emergency shutdown systems (ESSs), and automatic and manual suppression systems can be established and shown in the event tree time line. These response times are then used in the FPS performance success probability evaluation.

Threshold damage data, graphical exposure profile and event tree time line examples, and fire and explosion computer modeling are discussed in Chap. 5.

6. Fire Protection System (FPS) Performance Success Probability

FPS performance represents one of the dominant factors in the estimation of potential risk levels. Step 6 includes methods to quantify the conditional probability of performance success for a defined event scenario and established risk tolerance criteria. FPS of primary interest in fire risk-based evaluations include the following:

- Detection systems
- Emergency control systems
- Automatic suppression systems
- Propagation limiting measures (i.e., fire barriers)
- Manual loss control intervention

The methodology in Step 6, which centers around success tree analysis (STA) logic, can be used throughout the life cycle of fire protection systems to evaluate and quantify performance success. This approach can be applied to:

- **Evaluation of Existing Systems**
  This quantifies expected performance success of existing FPS when subjected to specific scenarios and risk tolerance criteria.
- **Evaluation of New System Designs or Modifications**
  This quantifies expected performance success of design options or alternatives to meet scenario-based "Performance Design Targets." For example, if the targeted performance success probability for a specific scenario is 0.99 (i.e., 99 out of 100 times it will be successful against this scenario), then design alternatives are evaluated in terms of response effectiveness, projected on-line availability, and estimated operational reliability to meet this performance target.

Step 6 involves the quantification of performance using three probabilistic measures:

- Response effectiveness
- On-line availability
- Operational reliability

Performance quantification methods and examples, failure rate data sources, data modification via the use of performance integrity measures, and integration of engineering judgement are discussed in Chap. 6.

7. Risk Estimation & Comparison With Risk Tolerance

Risk estimation and comparison provides the methodology for:

- Estimating consequence levels associated with defined event tree loss scenarios in terms of an equivalent monetary value and annualized risk basis
- Comparing the estimated risk to risk tolerance criteria to determine if risk reduction analysis is needed

Step 7 describes the risk estimation calculation steps using the ETA modeling framework. As part of the estimation process, the exposure levels developed in Step 5, Exposure Profile Modeling, are converted to equivalent monetary units. This provides a single measure of consequences, which allows risk to be calculated in terms of dollars at risk per year from fire or explosion potentials. Using an equivalent monetary measure of risk allows cost/benefit analysis to be performed on risk reduction alternatives when the decision makers' risk tolerance criteria are exceeded. Examples of graphical profiles of risk comparison are presented in Chap. 7, along with an overview and short examples of computer-assisted simulation to quantify risk uncertainty.

Uncertainty must be accounted for in the communication of risk estimation to the decision makers. Uncertainty assessment is a measure, qualitative or quantitative, of the degree of doubt or lack of certainty associated with risk estimating inputs, variables, probability values, deterministic models, and equivalent monetary values.

A quantitative uncertainty analysis can be performed within a computer spreadsheet program such as Microsoft Excel using what-if analysis or *Monte Carlo* simulations. An example of using *Monte Carlo* simulation is provided in Chap. 7.

8. Cost/Benefit Analysis of Risk Reduction Alternatives

The term "risk reduction" is defined as the application of technological or administrative measures to reduce fire or explosion risk to a tolerable level. Reduced fire risks mean fewer fire losses and claims, a more efficient operation, better employee morale, higher profits, better public relations, and greater investor confidence. However, these are not obtained without cost. Decision makers must recognize and quantify the risks and assess cost-effective approaches for reducing them. This is done by conducting cost/benefit analyses for risk reduction strategies and alternatives.

Risk reduction options in Step 8 include

- event likelihood reduction,
- fire protection system improvement, and
- consequence reduction.

The cost/benefit analysis process described in Chap. 8 consists of

- quantification of risk reduction alternatives,
- cost analysis for selected strategies,
- ranking of strategies by risk reduction/cost ratios, and
- decision analysis.

Chapter 8 provides an example of screening and quantifying risk reduction for alternative fire protection design strategies using a computer spreadsheet model.

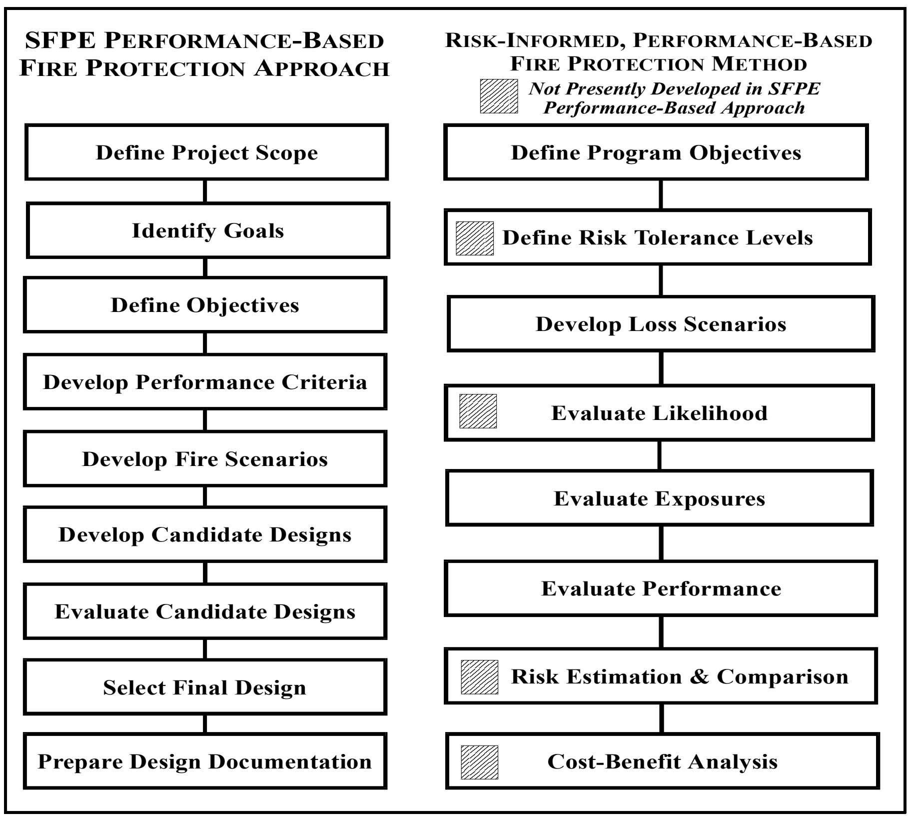
1.3.2 Comparison with the SFPE Performance-Based Approach

Figure 1.9 presents a side-by-side comparison of the Society of Fire Protection Engineering (SFPE) performance-based fire protection approach[3] and the risk-informed, performance-based fire protection method described in this book.

Steps not presently addressed in the SFPE approach include

- defining risk tolerance levels,
- evaluating event likelihoods,
- estimating and comparing risk, and
- conducting cost/benefit analysis.

Fig. 1.9: Method Comparison.



The primary differences between the SFPE performance-based method[3] and the risk-informed performance-based method described in this book are:

- the SFPE method is primarily based on a deterministic modeling approach, and
- the risk-informed, performance-based method, as described in this book, is based on a probabilistic risk-based modeling approach. Deterministic models (i.e., fire models) are used in this method to “support” probability and risk estimates.

From my experience at industrial facilities, decision makers want to know the risk (likelihood and consequences), risk-modification alternatives, and costs as part of their decision making process, thus the term “risk-informed.” FPS performance has numerous probabilistic variables and therefore should be evaluated as a “conditional probability” following defined functional requirements based on the specific scenario and quantitative risk tolerance criteria.

The following was extracted from the *Journal of Fire Protection Engineers*[4], an SFPE publication (underlining added for emphasis).

> *Although the use of deterministic calculations provides a picture of what the conditions in a room may be at a given time, or what the performance of individual structural components is, it has limited ability in considering the entire building with its fire protection systems, functions and occupants as a system. This limitation is significant as it does not allow the quantification of the overall safety level in a building. A comparison of alternative designs is limited only to specific elements. To obtain an overall assessment of building, deterministic computations must be combined with probabilistic analysis.*
>
> *In contrast to deterministic calculations, probabilistic methods may be able to consider the whole building (not element by element evaluation) and to provide risk estimates. In probabilistic evaluations, there are many factors that could affect the occurrence of a fire, its development and the egress of the occupants. The objective is to estimate risk levels using the likelihood of a fire incident occurring and its potential consequences (injury, death, etc.). The risk criteria can be established through statistical data, however, in order to gain society’s acceptance, such an approach must become widely used. The risk levels, calculated using probabilistic risk assessment methods, are then compared to the risk criteria to determine whether the proposed designs are acceptable. Presently, the probabilistic approach is rarely used because of the lack of appropriate risk assessment tools and the unavailability of specific risk levels acceptable to society. However, with the introduction of performance-based codes, the availability of risk assessment models and the establishment of risk levels acceptable to society, the probabilistic approach will be the preferred method in performance-based design as it quantifies the risk levels and allows the identification of designs that will have acceptable risk levels at minimum cost.*

1.4 PROJECT MANAGEMENT ISSUES

Implementation of an effective risk-informed, performance-based fire protection program requires good project management. Development and delivery of information in a timely and cost-effective manner requires

- project definition,
- project team selection,
- resource allocation, and
- risk communication.

1.4.1 Project Definition

Table 1.2 provides a general worksheet for defining risk-informed project parameters. If documented project definition is not provided at the start, the risk quantification process can become resource intensive.

1.4.2 Project Team Selection

The risk estimation process must include a team consensus approach. Team members should include representatives from the plant knowledgeable in the specific facility hazards, operations, and maintenance practices; representatives from environmental, safety, fire protection; and risk management and financial personnel.

Capabilities of the plant consensus team should include the features listed below.

- Knowledge of the facility, operations, equipment, and safety features under
  - normal operations and
  - abnormal emergency conditions;
- Experience with
  - plant loss incident history,
  - contributing factors to loss incidents, and
  - modifications and changes made following losses;
- Understanding of fault tree analysis (FTA) and event tree analysis (ETA) models including
  - a team leader with expertise in FTA and ETA and
  - team members with a rudimentary understanding of FTA and ETA concepts.

Table 1.2: Example Project Definition Worksheet

ISSUES	ANSWERS
1 What is the decision to be made? (Risk study goals)	
2. What is the focus of the assessment? (Risk study objectives)	
3. What are the system boundaries? (Scope of work, what's included, what's not)	
4. What are the values exposed within the defined boundaries? (People, property, production)	
5. What is the risk tolerance criteria? (Refer to Chap. 2 in this book)	
6. What is the level of detail?	
7. What are the manpower resources required? (Project team, plant site assistance)	
8. What consequence modeling tools will be needed?	
9. What sources of failure rate and reliability data are available?	
10. What other hardware, software, or other costs are needed to complete the project?	
11. What are the budget constraints?	
12. How will the "results" of the risk assessment be presented to management?	
13. What will be the procedures for interactive technical quality reviews and documentation?	
14. What are the schedule and delivery dates?	
REMARKS:	

1.4.3 Resource Allocation

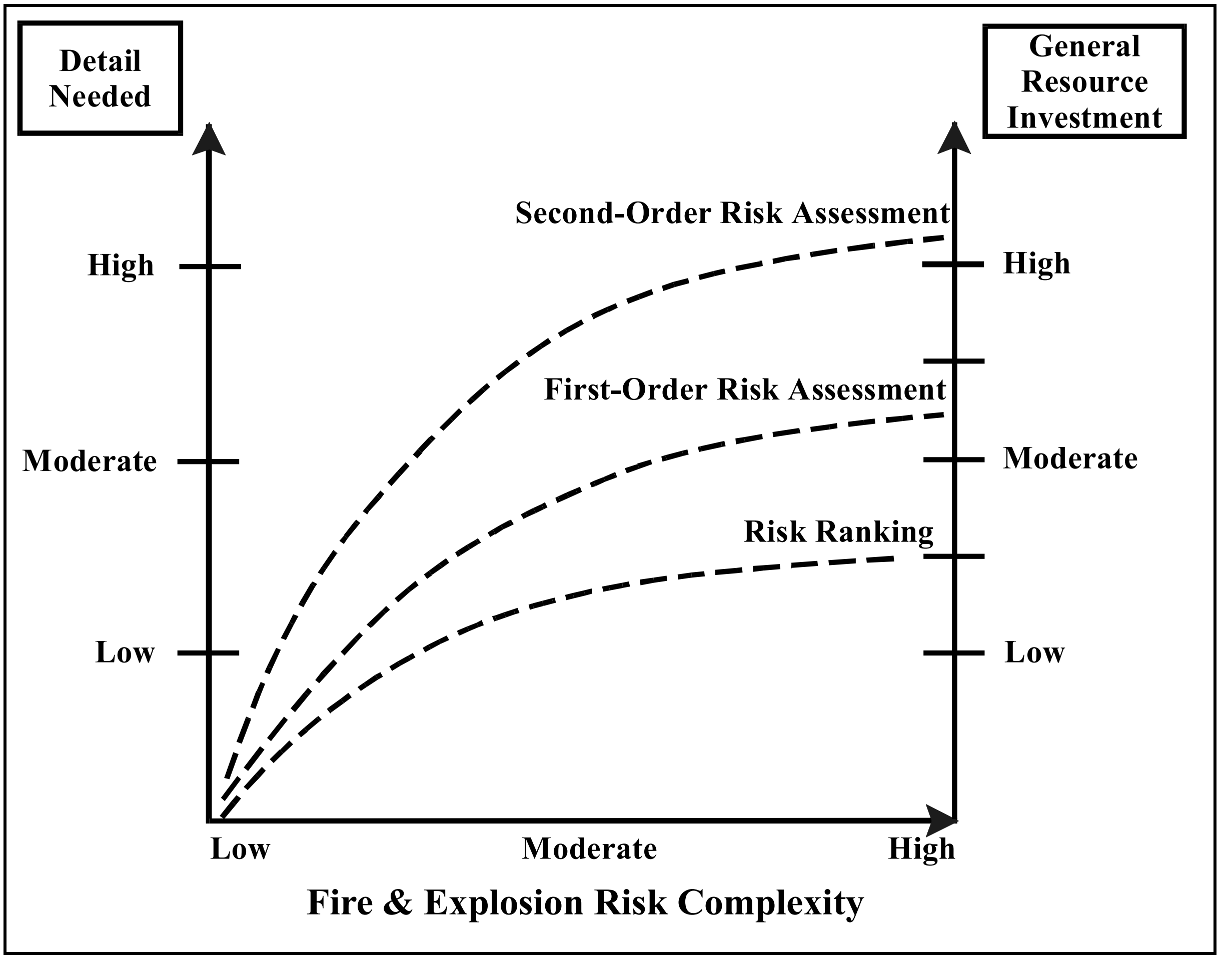
Resource allocation considerations should include:

1. Level of decision detail
    - decision complexity
    - decision importance
    - physical boundaries of study
    - accidents of interest (or excluded accidents)
    - methods for risk estimation and comparison
2. Expenditures
    - human resources
    - assessment tools
        i) computer models
        ii) research
        iii) testing
3. Constraints
    - time
    - budget

Figure 1.10 provides a general illustration of risk assessment resource investment levels. As depicted on Fig. 1.10, three general levels of detail are indicated:

- Risk ranking
- First-order risk assessment, and
- Second-order risk assessment

Fig. 1.10: General Illustration of Risk-Based Project Resource Investment



Risk ranking, which is the relative semiquantitative categorization of fire and explosion risks to identify, screen, and focus further efforts is addressed in Chap. 3, Loss Scenario Development.

First-order risk assessment is a term unique to this book. First-order assessments relate to structuring bounding scenarios and event trees that quantify significant risk contributors. This term will become clearer from the approaches described in this book. First-order assessments limit the detail to that needed to produce results within the project objectives and resource allocation constraints.

A second-order assessment involves additional detail. For example, it may entail application of finite-element heat transfer analysis to estimate a more accurate time of structure failure or very complex fault tree analysis of initiating failure events. If this level of detail is needed, then the additional time, modeling tools, and expenses must be weighed against the benefit of compiling this additional level of detail.

The application of a formalized, risk-based assessment is beneficial if the total risk reduction benefit of the effort exceeds the total costs. The costs include the time, resources, and costs associated with conducting the risk assessment project plus the cost related to the implementation of the risk reduction measures.

For example, if the cost to do the risk-based assessment (i.e., project cost) is $50,000 and the cost to implement risk reduction measures is $100,000, the total cost is $150,000. If the risk reduction benefit obtained is estimated at $75,000, then the benefit/cost ratio is $75,000/ $150,000 = 0.5. If the benefit/cost ratio is less than 1, then the risk assessment effort may not be considered beneficial. This is an important consideration that should be examined in Step 1.

An example of a successful, risk-informed, performance-based project follows. Plant management was being forced to take action on a recommendation to reinforce a sprinkler system (i.e., provide a higher sprinkler system design density) in a high-valued facility containing numerous hydraulically operated machines. The recommendation purpose was to improve protection against a hydraulic oil fire. Because the existing sprinkler protection was hydraulically designed at a lower sprinkler design density based on the available water supply, the completion of this recommendation would require replacing most of the existing sprinkler system and water supply improvements at a cost exceeding $150,000. In addition, the company had five other facilities that would require similar updating.

Plant management decided to conduct a fire risk assessment study to evaluate other possible risk reduction alternatives. The risk assessment followed the steps described in this book. The alternatives that resulted from the assessment focused on methods to prevent and reduce the severity of a hydraulic-oil torch fire situation. Alternatives included improved oil pressure instrumentation and equipment shutdown interlocks, barriers positioned to deflect pressurized oil releases, higher pressure flexible hydraulic hoses, and oil drain-down lines to a holding reservoir. By minimizing the torch-fire probability and consequential exposure radius and duration and by providing risk reduction measures that would modify an oil release from a torch to a limited pool fire configuration, the existing sprinkler system would be adequate in controlling the fire and minimizing damage.

The cost of the risk assessment study, which used first-order event trees and fault trees, was $28,000. The cost to make the improvements was approximately $60,000. The total cost was therefore $88,000 versus the $150,000 to reinforce the existing sprinkler system. For five facilities the overall cost savings were approximately $366,000. In addition, the alternative improvements afforded a much higher risk reduction to the operations and employees working in these facilities.

1.5 RISK COMMUNICATION

The results of the risk-informed performance-based project must be presented in a format understandable to the decision makers responsible for making the decisions and implementing the action plan. Table 1.3 lists some primary risk communication needs.

Table 1.3: Some Primary Decision Concerns Versus Risk Communication

DECISION CONCERNS	RISK COMMUNICATION
How serious are the fire and explosion exposures (on-site, off-site)?	Graphical fire and explosion risk profiles. Comparison with risk tolerance criteria
How beneficial are the proposed loss control recommendations?	Estimated change in risk for each proposed loss-control alternative or strategy
What regulatory implications (OSHA, EPA, building codes, etc.) are involved?	Regulatory compliance issues
How expensive are the proposed loss control recommendations?	Estimated initial and annual costs associated with risk reduction alternatives
Do the recommended changes represent an exception to existing corporate policies or safety standards? Will other similar plants, facilities, or operations be affected?	Identification of any potential conflicts with present policies or procedures. Potential total cost to the corporation for upgrading similar facilities

Graphical risk profiles, described in Chap. 7, Risk Estimation and Comparison, provide a good visual presentation format for communicating the following information to the decision makers:

- existing risk levels,
- modified risk levels based on proposed risk reduction alternatives,
- comparison of risk with management's established risk tolerance limits, and
- areas where further risk quantification may be needed.

An important point here is that the risk communication format must have the ability to "compare" existing and modified risk levels with established risk tolerance levels.

Some key project issues that should be addressed in Step 1 are listed here.

- The type of risk profile presentation format that will be used to aid management decision making
- Establishing management's risk tolerance limits for risk comparisons
- Availability of fire and explosion models or algorithms for determining the potential sizes of toxic or flammable vapor clouds, overpressure zones from explosions, fire intensities from building fire exposures, etc.
- Appropriate sources of failure rate and reliability data and selection methods to support probability modeling

- Research, data gathering, testing that may be needed to support consequence and probability modeling
- Incorporating human error and management factors into failure probability ranges.
- Procedures for addressing and presenting uncertainty
- Procedures for conducting interactive quality assurance reviews
- Methods for tracking the implementation of action plans

Risk-informed, performance-based program objectives involve:

- Establishing a risk-based decision making framework and team concept
- Applying a structured, consistent methodology and steps to quantify risk and perform risk reduction cost/benefit analysis
- Implementing an effective project management plan

Implementation of an effective risk-informed, performance-based fire protection program requires good project management that incorporates:

- project definition,
- project team selection,
- resource allocation, and
- risk communication.

Risk-informed, performance-based approaches should be considered tools to enhance and improve engineering judgements.

The following is extracted from reference [5]:

> *Quantitative analysis techniques have gained a great deal of popularity with decision makers and analysts in recent years. Unfortunately, many people have mistakenly assumed that these techniques are magic "black boxes" that unequivocally arrive at the correct answer or decision. No technique can make that claim. These techniques are tools that can be used to help make decisions and arrive at solutions. Like any tools, they can be used to good advantage by skilled practitioners, or they can be used to create havoc in the hands of the unskilled. In the context of Risk Analysis, quantitative tools should never be used as a replacement for personal judgment.*
>
> *Finally, you should recognize that Risk Analysis cannot guarantee that the action you choose to follow — even if skillfully chosen to suit your personal preferences — is the best action viewed from the perspective of hindsight. Hindsight implies perfect information, which you never have at the time the decision is made. You can be guaranteed, however, that you have chosen the best personal strategy given the information that is available to you. That's not a bad guarantee!*

The risk-informed, performance-based methodology discussed in this book is based on realistic experience and application. Application has included risk assessment and evaluation of fire and explosion prevention and protection systems in the chemical, oil, gas, nuclear, and electric power industries as well as hazardous material processes, storage, and other industrial production operations. The application of this methodology, although based on industrial-type risks, also lends itself to numerous commercial applications.

As for prescriptive codes, the movement will be more and more towards risk-informed, performance-based methods. Existing codes primarily concentrate on hardware design criteria based on loss experience. Most existing codes do not address risk tolerance criteria, scenario likelihoods, FPS response time of fire protection systems, system availability factors, and quantification of reliability versus common cause internal and external failures, human error, or FPS proof testing frequency versus reliability.

It is certainly expected that the methodology described in this book will be refined based on users' input and the progression of performance-based fire protection standards and applications. The current performance-based code thinking needs to extend beyond some of the current trends that primarily equate performance success to the results of deterministic fire modeling efforts. Performance success is a probabilistic measure. Risk tolerance criteria should dictate performance requirements. Adding risk-informed to the performance equation will allow for more flexibility in evaluating alternative fire protection designs and testing options and will lead to improved cost-effectiveness.

1.6 REFERENCES

1. Schmidt, Michael E. G. and Mauney, D. A. Sept. 1988. *How Financially Optimizing Maintenance Can Solve Your Safety Issues,* Proceedings: International Conference and Workshop on Reliability and Risk Management, Center for Chemical Process Safety of AIChE, New York, NY, 1989.

2. American Institute of Chemical Engineers (AIChE). *Center for Chemical Process Safety (CCPS), Guidelines for Chemical Process Quantitative Risk Analysis*, New York, NY, 1989.

3. National Fire Protection Association 2000. *SFPE Engineering Guide to Performance Based Fire Protection, Analysis and Design of Buildings*, Quincy, MA.

4. Hadjisophocleous, G. V., Benichou, N., and Tamim, A. S.,1998. "Literature Review of Performance-Based Fire Codes and Design Environment." *Journal of Fire Protection Engineering*, 9(1), pp. 12 – 40.

5. Palisade Corporation. *Guide To Using @ Risk; Risk Analysis and Simulation Add-In for Microsoft Excel or Lotus 1-2-3.* Newfield, NY, 1996.