SECTION 5

13 Risk-Informed Industrial Fire Protection Engineering

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Introduction

Risk-informed fire protection evaluation is a risk-based decision support tool that evaluates fire and explosion consequence likelihood and includes an analysis of fire protection system(s) performance reliability.[1]

The type of risk-based evaluation and level of detail should be dependent on the complexity of the risk and the needs of the decision maker. Table 5-13.1 lists three general levels of decisions to help decision makers choose an appropriate basis for their decisions.[2,3]

Based on the decision class, risk management goals, and risk-informed project objectives, the most efficient risk assessment and risk communication methods should be applied. The results must provide the information needed to make informed fire protection decisions based on risk tolerance and cost-effectiveness.

The risk-informed evaluation framework, presented in Figure 5-13.1, includes the following:

- Hazard evaluation
- Consequence analysis
- Fire risk evaluation method selection
- Risk-reduction decision making
- Risk monitoring

The purpose of this chapter is to provide an overview of fire risk-informed evaluation methods. References are included to allow the reader to pursue further detail. Emphasis is given to the fire risk evaluation method called fire protection system–layer of protection analysis (FPS-LOPA), which is becoming a popular approach for evaluating industrial process fire and explosion risks. An example FPS-LOPA is included in the chapter.

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Hazard Evaluation

All fire risk-informed methods start with hazard evaluation and consequence analysis. Risk-informed approaches supplement these evaluations but do not replace them.

The purpose of a hazard evaluation is to identify and analyze the hazards, identify initiating events and scenarios, and provide appropriate documentation. A hazard

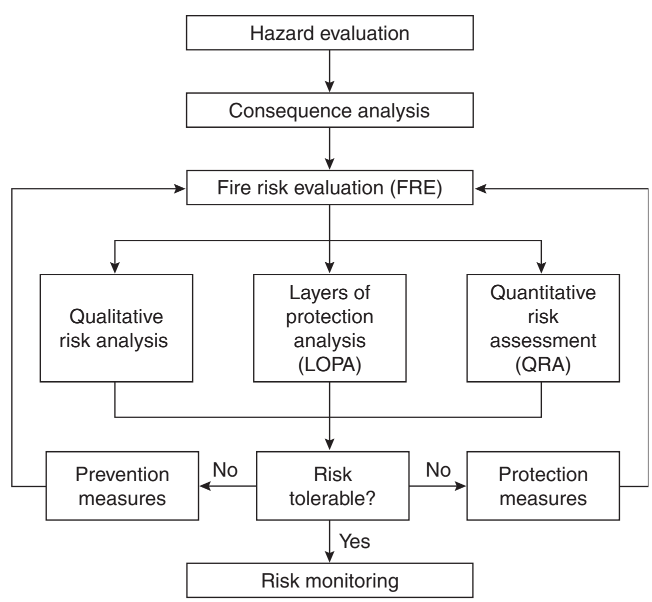

Figure 5-13.1. ***Risk-informed evaluation framework.***

Table 5-13.1 ***Decision Class and Fire Risk Assessment Approach***

Decision Class	Decision Context	Fire Risk Assessment Approach	Remarks
Class A	• Nothing new or unusual • Well-understood risk • Established risk	• Codes and standards • Good practice • Engineering judgment	Easiest to apply, generally uses qualitative risk analysis
Class B	• Life cycle implications • Some risk trade-offs • Some uncertainty or deviation from standard or best practice • Economic implications	• Fire protection system–layer of protection analysis (FPS-LOPA), which provides order-of-magnitude risk estimates based on specific cause-consequence scenarios	Simplified quantitative risk-informed evaluation methods are gaining popularity in the industry
Class C	• Very novel or challenging • Significant risk trade-offs • Large uncertainties • Strong stakeholder views or perceptions	• Quantitative risk assessment (QRA), which provides additional detail regarding event, contributing factors, risk reduction options, and cost-benefit analysis	Most demanding on resources and skill sets but delivers most detailed understanding and best decision basis if major expenditures are involved

evaluation can be conducted in any stage of design, operation, or decommissioning. In industrial applications, there are generally the following three types of hazard evaluations:

1. Process hazard analysis (PHA) using techniques such as the following:
   Hazard and operability analysis (HAZOP)
   What-if analysis
   What-if checklists[2]
2. Fire hazard analysis (FHA)
3. Special analysis
   Failure modes and effects analysis (FMEA)
   Human reliability analysis (HRA)

The most common hazard analysis and documentation techniques employed for industrial processes are what-if analysis and HAZOP. What-if analysis provides an adequate evaluation method for processes that are not highly complex and for processes that require a fair degree of operator monitoring and intervention. In general, for more complex processes, hazard and operability analysis (HAZOP) is typically used. For specific equipment failure mode analysis, failure mode and effect analysis (FMEA) is often used in combination with HAZOP or what-if analysis. Human reliability analysis is applied when operator actions are a critical component in the hazard evaluation. These methods are described in detail in *Guidelines for the Hazard Evaluation Procedures with Examples*,[4] Lees,[5] and Sutton.[6]

Fire hazard analysis (FHA) specifically focuses on fire and explosion hazards, protection features, scenarios, life safety, and property exposures, with fire protection recommendations. Numerous chapters in the *SFPE Fire Protection Engineering Handbook* and NFPA *Fire Protection Handbook®*,[7] Schroll,[8] and Zalosh[9] provide further information on industrial fire and explosion hazards.

Consequence Analysis

Consequence analysis is the process of determining the impact of initiating event scenarios to a defined target or targets independent of frequency and probability. Consequence analysis approaches range from the use of loss experience and historical data (e.g., plant or companywide loss experience, industry incident data, applicable generic accident data) to the application of deterministic fire and explosion models. Depending on consequence analysis complexity, models can range from the use of spreadsheet fire dynamics equations to zone models to computational fluid dynamics (CFD) models. In many cases consequence analysis involves a hybrid approach using available historical incident data, modeling tools, and engineering judgment to derive a consequence category.

Fire and explosion consequence analysis generally involves the evaluation of the following two segments:

- The rate of development of a hazardous environment (intensity, distance, time) within the boundaries of the predicted hazardous event, sometimes called the hazard footprint, hazard or consequence envelope, or consequence boundary. This is generally known as a physical effects severity measure. Physical effects can include thermal, combustion products, and/or overpressure effects.
- The susceptibility or vulnerability of people to harm; physical damage to equipment, stock, or structures; production downtime or business interruption; environmental damage; or other indirect losses such as loss of customers, regulator penalties or fines, or an overall financial impact estimate. This is generally known as a vulnerabilty measure. Overall vulnerability may be affected by variables such as the potential number of people present, evacuation capabilities, contingency plans to minimize business interruption, and so on.

When estimating consequence vulnerabilities levels for understanding by management decision makers, simplicity and consistency are key aspects. Whether it is a qualitative consequence analysis provided by a fire protection engineer or explosion expert or a deterministic first- or second-order modeling effort, the use of consequence categories provides a consistent approach and is a good risk management communication tool.

Table 5-13.2 ***Example Life Safety Exposure Categories***

Life Safety Exposure	General Definition	Remarks
1—Low	First aid (minor injury associated with fighting fires or evacuation)	
2—Moderate	Single-person injury requiring hospital treatment	
3—Heavy	Multiple-person injuries requiring hospital treatment	
4—High	Life-threatening injury or death on-site	
5—Major	Life-threatening injury or death off-site	

Life safety exposure and consequence levels can be broken down into categories related to injury or fatality potential to operators, employees, on-site contractors, and off-site exposure to the public. Table 5-13.2 presents a general example of establishing life safety exposure and consequence levels.[1]

Property damage impact levels can also be broken down into categories as shown in Table 5-13.3.[1]

Consequence categories can also be set up for production downtime, environmental damage potential, and other various direct and indirect financial impacts, regulatory penalties or fines, media reaction, and/or loss of customers, financial (economic) impact, and so on.[1]

Target threshold damage limits are generally used to provide the link between physical effects (thermal effects, products of combustion, explosion overpressure, domino effects such as chemical or radiological releases, etc.), which are usually derived from fire and explosion modeling and potential end consequences (life safety injuries or fatalities, property damage, production downtime, environmental impacts, etc.). Fire and explosion modeling techniques are discussed in many chapters of the *SFPE Fire Protection Engineering Handbook*, as well as elsewhere.[1,5,10–12]

Fire Risk Evaluation Method Selection

Risk is the product of the expected frequency (events/year) and consequences (effects/event) of a single accident or group of accidents. The equation is generally shown as

$$\text{Risk}_{\text{accident scenario}} = \text{Event frequency} \times \text{Expected consequence(s)}$$

For a group of accident scenarios, which could affect a defined target area, the equation can be expressed as

$$\text{Risk} = \sum_{\text{scenarios}} \text{Event frequency} \times \text{Expected consequence(s)}$$

In fire risk-informed evaluations we are concerned with how the performance of fire protection systems mitigates an existing risk level. Mitigated risk requires the evaluation of the following three components:

- Frequency or likelihood of the initiating event
- Probability of the failure of fire protection system performance
- Expected consequence(s)

Table 5-13.3 ***Example Property Damage Impact Categories***

Property Damage Levels	Damage Factor Range (%)	General Definition	Remarks
1—Slight	0–1	Limited localized minor damage, not requiring repair	
2—Light	1–10	Significant localized damage of some components, generally not requiring major repair	
3—Moderate	10–25	Significant localized damage of many components warranting repair	
4—Heavy	25–60	Extensive process equipment damage requiring major repairs	
5—Major	60–100	Major widespread damage including major structural damage	

The risk associated with the potential realization of an undesirable consequence level, taking the performance of fire protection systems into account, can be shown as

$$\text{Risk}_{\text{accident scenario}} = \text{Initiating event frequency} \times \text{Probability of FPS performance failure} \times \text{Expected consequence(s)}$$

The three primary risk methods or risk assessment techniques that are addressed in this chapter include the following:

- Qualitative risk analysis (for Class A decisions)
- Fire protection system–layer of protection analysis (for Class B decisions)
- Quantitative risk assessment (for Class C decisions)

Class A Decisions: Qualitative Risk Analysis

Qualitative risk analysis is an extension of the hazard evaluation and consequence analysis, and is primarily conducted for risk screening, risk ranking, and recommendation prioritization activities. Basis can be unmitigated risk, mitigated risk, or both to show the relative change in risk with mitigation measures.

This method normally employs the following:

- Consequence category tables (refer to example Tables 5-13.2 and 5-13.3)
- Event likelihood category tables (refer to example Table 5-13.4)
- Risk classification matrix (refer to Figure 5-13.2)
- Associated risk class action matrix (refer to Table 5-13.5)

Table 5-13.4 provides an example of likelihood categories.[1]

Figure 5-13.2 presents an example of a risk classification table. In this particular example, life safety consequences and property damage categories are labeled on the same matrix for illustration purposes.

Table 5-13.5 presents an example of a risk class action table. This table lists action items associated with the risk classifications presented in Figure 5-13.2.

Qualitative risk methods usually employ consequence categories, event likelihood ranges with qualitative descriptors, and simplified risk matrix–action item tables.

Table 5-13.4 ***Example Event Likelihood Categories***

Likelihood	General Definition
1—Very low	Very remote possibility of occurrence (e.g., 1/300 to 1/1000 years)
2—Low	Possibility of occurrence once over two to three times the useful life of the process (e.g., 1/100 years)
3—Moderate	Possibility of occurrence once over the lifetime of the process (e.g., 1/30 years)
4—High	Possibility of occurrence once per average process life cycle (e.g., 1/15 years)
5—Very high	Occasional possibility of occurrence (e.g., 1/5 years)

Life safety consequence categories

Initiating event likelihood categories	1	2	3	4	5
5	A	B	B	C	D
4	A	B	B	C	D
3	A	A	B	C	D
2	A	A	A	B	C
1	A	A	A	B	C
	1	2	3	4	5

Property damage categories

Figure 5-13.2. ***Risk classification screening matrix.***

Team members' experience with similar events will have a major impact on their judgment. It is sometimes difficult to visualize and judge the risk of events that have not occurred at the plant. Uncertainty in risk judgments seems to increase for more complex scenarios and moderate to high consequences in terms of how much credit should be given to risk mitigation measures (i.e., fire protection systems). Because of this uncertainty, many scenarios fall into a risk classification action (such as Risk Class C in Table 5-13.5), which recommends further detailed risk analysis (i.e., may lead to a resource-intensive QRA). Therefore, it was clear to the chemical process industry that an intermediate risk analysis method was needed, one that provided additional information on the performance of independent risk reduction measures as related to specific scenarios. This spurred the development of layer of protection analysis (LOPA), which is discussed next.

Class B Decisions: FPS-LOPA

FPS-LOPA Basics

Fire protection system–layer of protection analysis (FPS-LOPA) goes beyond the typical use of a qualitative risk matrix but is less detailed than quantitative risk anal-

Table 5-13.5 ***Risk Classification Actions***

Risk Class	General Description	Actions
A	Low-risk events	Require no further risk reduction actions
B	Low- to moderate-risk events	Require minor risk reduction improvements; generally addressed by codes, standards, industry practices, and engineering judgment
C	Moderate- to high-risk events	Require further analysis to determine an optimal risk reduction strategy or analysis of the performance and reliability of risk controls
D	High-risk events	Require immediate risk reduction analysis

ysis (QRA). FPS-LOPA provides an order-of-magnitude risk analysis tool. It addresses the fire risk mitigation equation by separating the question of "how likely is it?" into the following two components:[13]

- Likelihood (frequency) of the initiating fire event
- Probability of failure on demand (P_{fod}) of independent fire protection layers (IFPLs)

This method has proven to be an effective tool to determine whether there are enough protection layers and sufficient risk reduction to meet the risk tolerance criteria for scenarios developed from process hazard analysis (PHA) and fire hazard analysis (FHA) information. The method uses event tree logic in a table or spreadsheet format to assess moderate to high fire or explosion consequences in terms of the likelihood of occurrence. The initiating event likelihood and the probability of success of fire protection systems are evaluated quantitatively and compared to risk tolerance criteria to determine if additional fire protection layers are needed. Figure 5-13.3 illustrates typical risk reduction layers at industrial facilities.

Prevention measures can be defined as the act of causing an event not to happen and can include elimination of hazards, ignition source controls, and procedural methods such as combustible control measures.

Mitigation systems are related to measures that cause a consequence to be less severe and generally include passive protection systems, detection systems and active engineering controls, active suppression systems, and procedural systems.

- *Passive protection systems.* Systems that reduce consequences without the active functioning of any device, such as dikes, blast walls, fire barrier walls, and so on
- *Detection systems and active engineering controls.* Detection and alarms, controls, safety interlocks, and emergency shutdown systems designed to detect potentially hazardous process deviations, conditions, or equipment malfunctions and to take corrective action, including pressure relief devices; gas, smoke, and fire detection and alarm systems; emergency shutdown systems; smoke exhaust/control systems, and so on
- *Active suppression systems.* Active suppression systems may include both automatic and manual systems: automatic systems may include sprinkler and water spray deluge systems, foam systems, gas extinguishing systems, and so on; manual suppression may include responses from operators, plant fire brigade, and public fire department
- *Procedural systems.* Operating procedures, administrative checks, plant site emergency responses, and other management approaches to minimize the severity of an incident

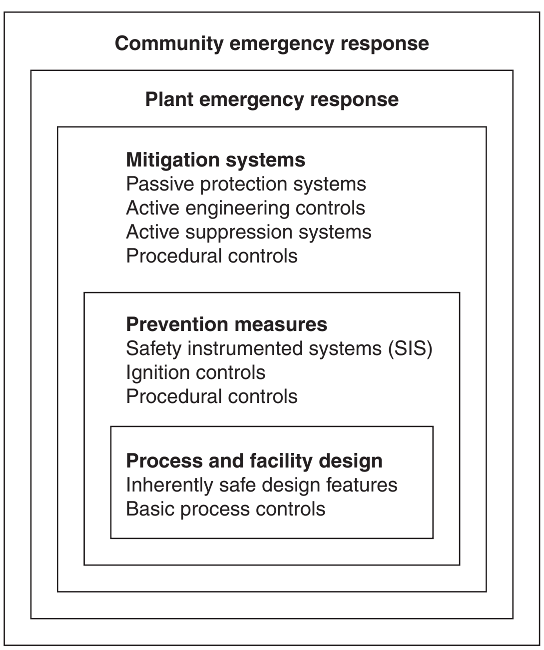

Figure 5-13.3. ***Typical risk reduction layers at industrial facilities.***

Discussions regarding the amount or layers of fire protection needed can result in heated debates when approached on a purely qualitative basis. Underprotection (too few layers) can potentially lead to loss of life, excessive property damage, and unexpected business interruption. Overprotection (too many layers) can lead to increased and unwarranted costs. Industrial plant risk management decision makers have to live within the constraints of available time, money, and resources. A common question is whether the company's money should be invested in prevention, mitigation, or emergency response. For example, if a system is designed to prevent a fire and provide passive mitigation features, then why are active mitigation features or additional plant fire brigade improvements necessary? Or if there is an active mitigation system, such as a sprinkler system, why are any additional fire protection features needed?

From a fire or explosion risk analyst's viewpoint, the degree of reason (need for mitigation layering) is based on the potential consequence levels, likelihood of realizing the consequences (risk level), confidence in the performance of fire protection measures (effectiveness, reliability), degree of human element involved in the scenario, and degree of risk tolerance. Inherently safe design and prevention measures should receive first attention and should be evaluated and documented through the process hazard analysis and fire hazard analysis to verify that the design features minimize the potential occurrence of a fire or explosion event.

Mitigation systems usually receive attention next and are evaluated in terms of independent fire protection layers (IFPLs): how much passive protection, how many active engineering controls, what type and how many active suppression systems, and how much procedural action will be needed. Emergency response from internally funded plant fire brigades generally receives next consideration along with public fire department response.

Several reasons not to rely on one type of fire protection, especially when dealing with uncertain fire or explosion risks, include the following:

1. No one independent fire protection system is perfect, meaning that 100 percent performance, 100 percent of the time is not possible.
2. Fire protection systems are subject to human error (e.g., fire door blocked open, etc.).

3. Arson or security breaches can compromise a fire protection system.
4. Inspection, maintenance, and testing deficiencies can reduce the performance reliability of a fire protection system.
5. Explosion overpressures can render a fire protection system inoperative.

These items should especially be kept in mind when developing a performance-based fire protection system design for moderate-high fire or explosion risks. This not only applies to industrial facilities but also should apply to high-rise buildings, health care facilities, airports, large assembly areas, and so on where the life safety consequences of a fire are high.

LOPA Definition and Steps

Layer of protection analysis (LOPA) defines risk as the likelihood of a specific consequence resulting from a postulated hazardous incident scenario. LOPA involves identifying initiating events, assessing existing or proposed layers of safety-related controls, and establishing tolerable frequency targets for people, property, or business interruption exposure. *Layers of Protection Analysis*[14] and Dowell[15] provide information on LOPA methods.

LOPA is a useful tool for prioritizing hazard scenarios and supporting risk-based decisions regarding the most cost-effective measures to meet risk tolerance criteria. LOPA is becoming a popular and widely used tool in the chemical, oil, gas, nuclear, and various high-tech industries. In the nuclear fuels processing industry a similar approach called risk indexing is required by the Nuclear Regulatory Agency as part of integrated safety assessments.

The Center for Chemical Process Safety (CCPS) book, *Layer of Protection Analysis, Simplified Process Risk Assessment*, states "The techniques of LOPA can be extended to most any type of risk reduction decision."[14] LOPA methodology, whose most common application has been in the evaluation of the release of hazardous chemicals, is being applied more and more to postignition fire scenarios, pre- and postexplosion scenarios, and evaluation of emergency action plans following fire or explosion incidents. LOPA methods are also being applied to the evaluation of security failure scenarios, which could lead to terrorist-caused toxic material, fire, or explosion exposures. This type of evaluation is known as rings of protection analysis, the security equivalent of LOPA.[16]

Fire protection system–layer of protection analysis (FPS-LOPA) is used in this chapter to focus on the evaluation of fire protection systems. FPS-LOPA provides a rational, objective, and simplified risk-based approach for decision making on the fire protection layers needed for specific scenarios to meet established risk tolerance criteria.

The steps involved in conducting an FPS-LOPA evaluation include the following:

1. Develop accident scenarios
2. Determine initiating fire event likelihood (events/year)
3. Quantify the performance of independent fire protection layers (IFPLs)
4. Evaluate target vulnerability
5. Estimate scenario risk
6. Conduct risk tolerance comparison
7. Make decisions on risk reduction
8. Monitor the risk

Step 1: Develop Accident Scenarios

Once a scenario has been identified and screened as a candidate for fire or explosion risk evaluation, it must be further developed and documented to a level where an understanding of the initiating events, enabling events, and independent fire protection layers (IFPLs) is achieved.

The primary components of FPS-LOPA scenario development are the following:

- Initiating event
- Enabling event(s)
- Independent fire protection system layer(s) (IFPLs)

FPS-LOPA follows an event tree calculation approach toward quantifying the likelihood of a specific cause-consequence scenario with a primary focus on the performance reliability (or probability of performance failure) of independent fire protection layers. Figure 5-13.4 illustrates an event tree showing the effect of IFPL success or failure.

As indicated, FPS-LOPA estimates the likelihood of an undesirable consequence occurring by applying a similar approach and calculation methods used in typical fire event tree analysis. As shown in Figure 5-13.5, branch 3 logic indicates occurrence of an undesirable consequence in terms of an uncontrolled high-exposure fire. For this example, the likelihood of this event scenario occurring is predicated on failure of two independent protection layers: failure of (B) emergency control system, and failure of (C) fire suppression system.

The math in Figure 5-13.5 for the uncontrolled high-exposure fire is as follows:

$$\begin{aligned}&\text{Likelihood}_{\text{uncontrolled high-exposure fire}}\\&= (A1)\times(B2)\times(C2) = 0.03\ \text{fires/yr}\\&\times 0.10\times 0.15 = 4.5\times 10^{-4}\ \text{events/yr}\end{aligned}$$

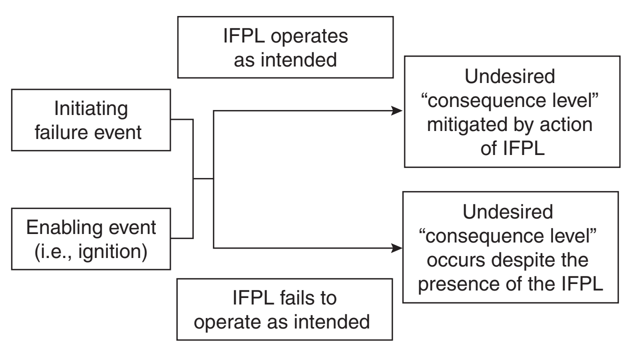

Figure 5-13.4. ***Effect of IFPL failing to operate as intended.***

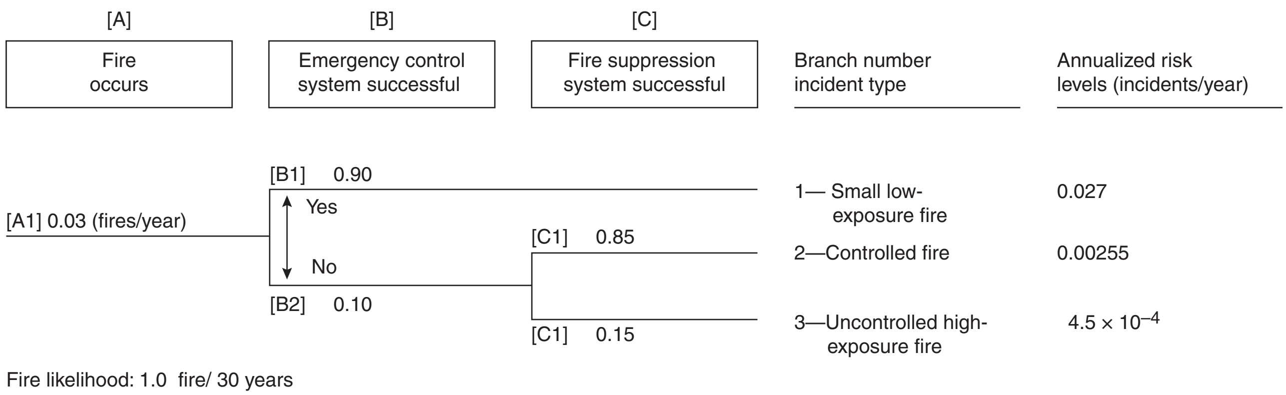

Figure 5-13.5. ***Example of a simple fire event tree.***

FPS-LOPA specifically focuses on the cause-consequence scenario pathway that leads to the high-exposure or high-consequence event, as shown in Figure 5-13.6. In most cases it evaluates the likelihood of reaching that upper-bound credible or worst-case credible consequence.

Information extracted from hazard evaluations, including what-if analysis, HAZOP, fire hazard analysis, or insurance probable maximum loss reports, can form the basis for the FPS-LOPA cause-consequence scenario selection and development.[1,17]

Step 2: Determine Initiating Fire Event Likelihood

$$\text{Fire}_{\text{likelihood}} = \text{Initiating event failure frequency (i.e., component failure, human error)} \times \text{Ignition probability (i.e., enabling event)}$$

In most cases, when evaluating industrial processes, the primary component failure is viewed as the initiating event and ignition is the enabling event leading to a fire scenario. They are usually evaluated separately in terms of initiating event frequency and enabling event probability. In rare cases, applicable confident fire statistics may be available and can be input directly into the FPS-LOPA evaluation as the initiating fire event frequency.

For industrial FPS-LOPA evaluations, initiating events of concern are generally related to equipment component failures or human errors that cause the release or availability of flammable or highly combustible materials, which could lead to major fire or explosion incidents. These incidents usually present bounding-type scenarios in terms of people and property damage exposure.

Equipment component failure rates and human error data are extracted from plant-specific records, industry failure data, and/or generic failure databases. Table 5-13.6 presents an example of some equipment component failure rate ranges.[14]

It is preferable to extract equipment component failure rate data from plant-specific data sources. The best sources of data are obtainable from operational and maintenance logs, other records, and interviews conducted with experienced plant personnel. Engineering judgments concerning the use and adjustment of these data can be based on plant surveys, available data, interviews, and experience. Some published failure rate data are provided in Barry,[1] *Guidelines for Process Equipment Reliability Data*,[18] *Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component*,[19] and *Offshore Reliability Data Handbook*.[20]

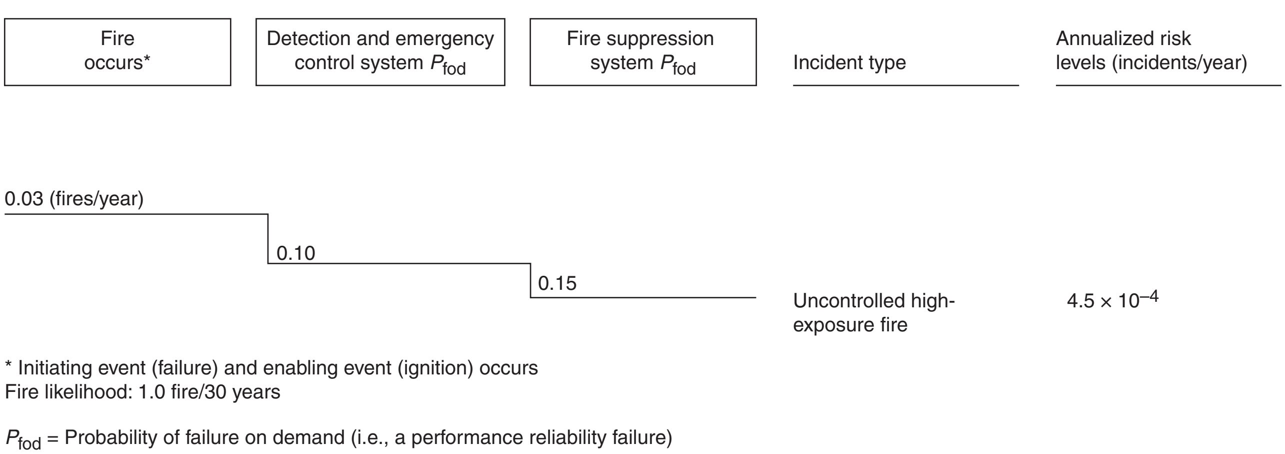

Figure 5-13.6. ***Example of the correlation between a simple fire event tree and FPS-LOPA.***

Table 5-13.6 ***Example of Some Initiating Event Frequency Ranges***

Initiating Event	Frequency Range from Literature (events/year)
Piping leak (10% section)—100 m	10^{-3} to 10^{-4}
Atmospheric tank failure	10^{-3} to 10^{-5}
Gasket/packing blowout	10^{-2} to 10^{-6}
Turbine/diesel engine overspeed with casing breach	10^{-3} to 10^{-4}
Safety valve opening spuriously	10^{-2} to 10^{-4}
Pump seal failure	10^{-1} to 10^{-2}
Unloading/loading hose failure	1 to 10^{-2}
Basic process control system (BPCS) instrument loop failure	1 to 10^{-2}
Regulator failure	1 to 10^{-1}

Human error: Human error probabilities are generally estimated from actual operating experience, task simulation, or expert opinion. Data derived from actual operating experience are best, but sufficient data may not be available. Expert opinion is acceptable and useful if a consistent methodology is applied within a team consensus framework. Based on review of numerous human error and human reliability references, Figure 5-13.7 presents an example of human failure probability ranges for the following three cases:[1]

1. Unplanned emergencies (i.e., postfire or explosion)
2. Routine oversight (normal operations)
3. Error in operator judgment

Within each case (i.e., probability range) there is a midpoint range and upper and lower bounds that relate knowledge, experience, and training factors. How often an operation is performed, stress factors, and other relevant performance-shaping factors should also be considered. The important part in human error probability estimation is to recognize the contributing factors and to apply a credible and consistent evaluation method.

Enabling event—probability of ignition: Characterizing the probability of ignition following an equipment failure or human error scenario starts with the identification and understanding of relevant ignition sources within the FPS-LOPA evaluation boundaries. This approach includes the following:

- Identifying ignition sources (fixed, mobile, variable) within defined exposure boundaries
- Evaluating ignition source strength (temperature, energy) in relation to the fuel's ignition sensitivity

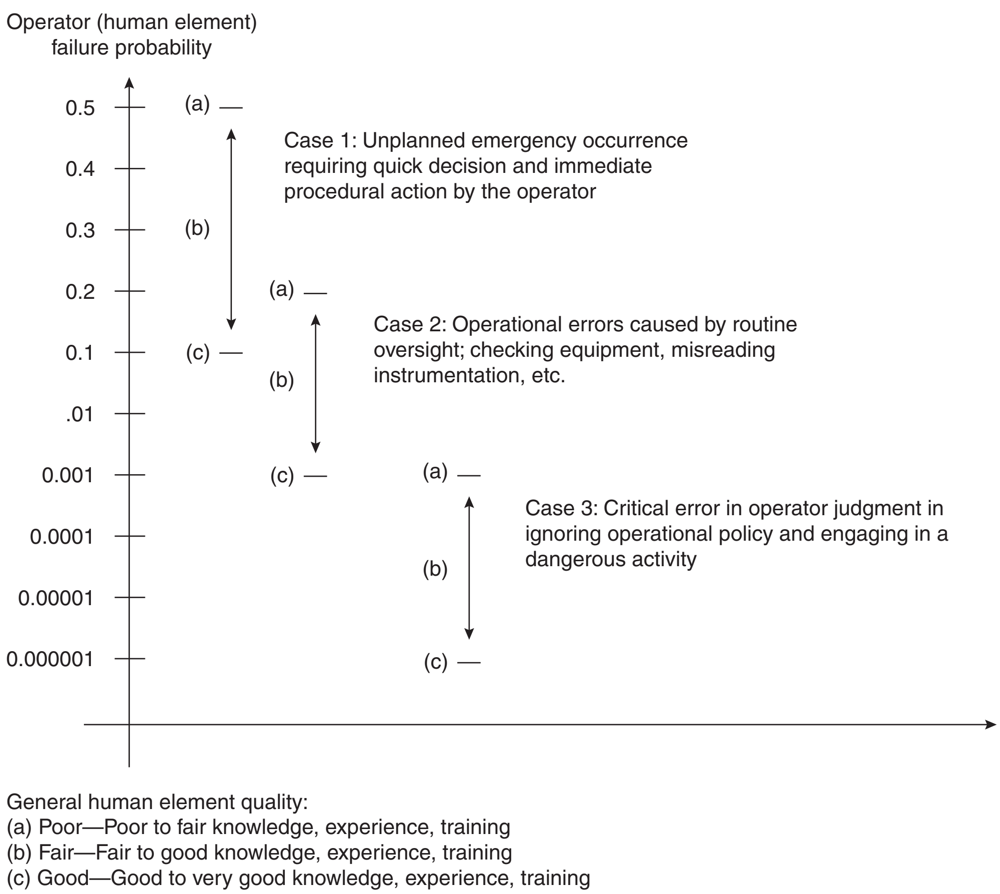

Figure 5-13.7. ***Example of human failure probability ranges.***

- Estimating the frequency of time the ignition source is present

In addition to reviewing available historical fire incident data that may describe ignition factors for similar scenarios, a plant survey of the area under FPS-LOPA evaluation should be conducted to identify and evaluate specific ignition source potentials. Based on engineering review and evaluation, identified ignition sources can then be categorized in terms of availability, source strength, and ignition probability. Table 5-13.7 provides an example of ranking ignition source strengths in categories and relating ignition probability ranges.[1]

Support sources for ignition identification and availability (i.e., frequency that ignition source is present) include the following:

- Identification of plant specific ignition sources
  - Plant survey
  - Plant records
  - Plant interviews
- Review of available industry or generic historical incident ignition data sources similar to the hazard/ignition potentials being evaluated
  - Identification of major ignition contributing factors
  - Ignition flame spread propagation potentials

Various sections in the *SFPE Fire Protection Engineering Handbook,* Lees,[5] and the NFPA *Fire Protection Handbook,*[7] provide information on ignition sources. *Ignition Handbook*[21] provides a comprehensive examination of ignition dynamics. Barry[1] provides information on characterizing potential ignition likelihood.

Step 3: Quantify the Performance of Independent Fire Protection Layers (IFPLs)

An independent fire protection layer (IFPL) is a device, system, or action that is capable of preventing a scenario from proceeding to the undesired consequence level regardless of the initiating event frequency or the action of any other fire protection layer associated with the scenario. In addition, the effectiveness and independence of an IFPL must be auditable. The audit process confirms that the IFPL design, installation, and functional testing and maintenance systems are in place to achieve the specified performance reliability for the IFPL.[14]

In a standard LOPA evaluation, usually conducted for chemical process hazards, the focus is on measures to prevent a consequence, such as a toxic chemical release or explosion, via instrumentation, emergency isolation valves, pressure relief valves, and so on. A major assumption is that the protection safeguard is designed to perform its intended function in an effective manner and, therefore, only the operational reliability parameter is estimated.[22]

Table 5-13.7 ***Example Ignition Source Strength vs. Ignition Probability Range***

Ignition Source Strength Ranking	Ignition Probability Ranges
Strong (S)	0.25–1.0
Medium (M)	0.05–0.24
Weak (W)	0.01–0.049

Operational reliability is a measure of the probability that a protection system will operate as intended when needed. Performance reliability is a measure of the adequacy of the system to successfully perform its intended function under specific fire scenario conditions. Performance reliability, or the probability of success of a fire protection system to perform its functional performance objectives, includes both operational reliability and design effectiveness parameters.

The probability of failure of a fire protection system (P_{fod}) is the failure of the protection measure to perform its designed functional performance requirement to mitigate a scenario consequence. Fire protection systems are usually evaluated in terms of their probability of performance success (i.e., they performed their functional performance requirement as intended). The correlation here is

$$\text{Probability of success} = 1.0 - \text{Probability of failure}$$

For example, if the probability of failure due to design ineffectiveness, response time, unavailability, or operational reliability is estimated at 0.10, meaning that it may fail to perform its full functional requirements 1 out of 10 times, then the probability of success is estimated at 0.90, meaning that 9 out of 10 times it should perform successfully in meeting its functional performance requirements.

As fire protection systems (FPS) are mitigation systems, they must be viewed in terms of a performance-based reliability, which incorporates design effectiveness and operational reliability. In FPS-LOPA we are interested in the probability of success of an FPS meeting its functional performance objectives and are thus concerned with estimating the performance reliability. This is generally approached in the following ways:

1. Using historical operational reliability data (statistical data from plant records, industry data, generic databases, published equipment or component failure rate data tables) along with an analysis of the design effectiveness to meet the functional performance objectives for the specific FPS-LOPA scenario
2. Using an engineering assessment model to evaluate a performance integrity level (PIL) that is used to select performance reliability from within a range of failure probability categories, which are established from Item 1 type sources and engineering judgment
3. Using qualitative fault tree analysis (FTA) to identify contributing factors to the success or failure of the IFPL, and then using Item 1 and Item 2 sources and methods toward quantitative estimation

Operational reliability data and engineering design assessment: Statistical data on the performance of fire protection systems under exact or comparable scenario conditions are generally hard to find. Bukowski et al.[23] and British Standard 7974[24] are often cited when first-order estimates are applied in fire risk assessments. Both references are based on compilation of available statistics from worldwide sources and expert opinion surveys. Both references use many of the same sources and, therefore, the data are fairly comparable. Bukowski et al.[23] provides a definition and distinction between operational reliability (operates as intended) and performance reliability (meets a performance requirement) and indicates data are based on operational reliability statistics. Table 5-13.8 provides a range of operational reliability data from published estimates.[23]

It should be noted that the majority of data were compiled from residential, commercial, and institutional occupancies. The data do, however, provide an insight into an operational reliability range or bandwidth for the selected fire protection systems.

When using such data in an FPS-LOPA evaluation, selection of either an upper or lower bound for the operational reliability is generally done by conducting a survey of the installation quality and evaluating the inspection, testing, and maintenance (IMT) program. The design effectiveness is based on an engineering design evaluation and may incorporate deterministic modeling to evaluate the protection system response to the specific scenario. Uncertainty in the design effectiveness may be expressed probabilistically based on engineering evaluation and judgment. The combination of the design effectiveness (P_{de}) and operational reliability (P_{or}) probabilities can be expressed as

$$\text{Fire protection system (FPS) performance reliability} = P_{de} \times P_{or}$$

For example, if the FPS design effectiveness was evaluated by an engineer who graded the P_{de} at 0.99 and selected P_{or} at 0.95 for the specific scenario, the FPS performance reliability would be estimated as

$$\text{FPS performance reliability} = 0.99 \times 0.95 = 0.94$$

This result would indicate that the FPS should meet the functional performance objectives for the specific scenario 94 out of 100 times.

Table 5-13.8 ***Some Operational Reliability Ranges***

Fire Protection System	Operational Reliability Probability of Success (%)	General Criteria
Automatic sprinkler systems	95–97	Sprinklers operate
Masonry construction	70–95	Limit flame spread, maintain structural integrity
Gypsum partitions	69–95	Limit flame spread, compartmentation
Heat detection systems	89–95	Notify occupants and fire service
Smoke detection systems	70–90	Notify occupants and fire service

Developing an engineering assessment model to evaluate a performance integrity level: An engineering assessment approach that incorporates a performance-integrity basis can be applied in an FPS-LOPA evaluation. To develop a relationship between performance integrity levels (PILs) and performance reliability, the following actions are recommended:

- Conduct a code and practices compliance review
- Evaluate performance integrity measures (PIMs), based on a site-specific survey
- Assess the quality of the inspection, maintenance, and testing (IMT) program

Current codes such as mechanical, plumbing, or electrical codes, along with specific National Fire Protection Association (NFPA) standards, provide various levels of FPS design criteria. In addition, some industry associations and property insurance companies provide interpretive guides to certain NFPA standards and “good practice” design supplements based on lessons learned from fire and explosion losses.

In general, design criteria developed by these sources focus on equipment, components and materials of construction, installation requirements, and acceptance testing. Normally, very little information is provided on FPS performance factors such as the following:

- System response time design guidance and quantification methods
- Online availability issues such as design factors, which could minimize downtime
- Failure rate data references for systems, equipment, components
- Common cause failure effects (i.e., corrosion, freezing, etc.)
- Relationship of system reliability versus various design enhancement options
- Effect of inspection, maintenance, and testing on FPS reliability

What FPS design codes and standards do provide, however, is design guidance based on past failure experience; therefore, in a qualitative sense, they provide a level of reliability. In addition, FPS equipment and components must be listed or approved by nationally recognized testing laboratories.

Some primary performance integrity measures (PIMs) for FPS evaluation might also include the following:

- Design suitability, capacity, and duration for the specific hazard being evaluated
- Installation: certified installers, quality control, full acceptance test
- Response time: meets functional response time objectives
- Management of change (MOC) program: a written procedure in place for hazard review versus FPS performance
- Online availability: not subject to excessive IMT downtime, false-trip downtime, physical damage unscheduled downtime, external common cause exposure downtime, such as freezing weather, and so on

- Life cycle: age of components, repair-replacement program
- Operating environment: subject to abnormal temperatures, dust, corrosion, vibration, and so on
- Continuous online diagnostics (i.e., continuous electronic fault detection, supervision)
- Redundancy features (redundant components, secondary power supply, etc.)

Operational reliability is impacted by the frequency of proof testing as well as by the failure rate of FPS components. For fire protection systems, documenting the required test interval and test procedure associated with a required reliability and performance level is critical. The test procedure must prove the correct functioning of all parts of the FPS (i.e., input devices, control unit, and output functions). Proof testing is particularly important for detecting hidden failures that may not be revealed during normal operations.

An engineering-based performance reliability model: Barry[1] discusses the use of engineering evaluation scoring models, using grading and importance weighting measures to relate PIM quality scores for adjusting and selecting FPS failure rates (or performance success probability) from a range of generic data or statistical data bandwidths.

Using an engineering evaluation model, based on site-specific assessment, to select an FPS performance success probability may in many cases be a better choice at an industrial facility than trying to rely on some generic operational reliability statistics.

Table 5-13.9 presents a generic example of relating performance measures to a performance success probability range. (This table is shown solely for example purposes.) The last column provides performance reliability ranges in terms of performance success probability. Again, performance reliability is based on meeting functional performance objectives or requirements based on a specific scenario.

Fault tree analysis: Qualitative fault tree analysis (FTA) is a good tool for breaking down the contributing component failures that could lead to failure of a fire protection system. FTA can assist in the understanding of the components and factors that affect performance reliability parameters such as design effectiveness, online availability, and operational reliability. This analysis provides supplemental information for assessing FPS operational reliability. FTA quantification is not usually done in an FPS-LOPA but can be used to supplement an evaluation of a complex FPS if warranted.

Use of engineering judgment and subjective probabilities: In most cases a hybrid approach must be taken to estimate FPS performance reliability. A hybrid approach generally uses available frequency or probability data, engineering-based assessments and models, and engineering judgment to estimate FPS performance reliability as related to a specific scenario. Subjective engineering judgment, when used in a structured and consistent manner, has great value in understanding FPS performance under specified scenario conditions and for documenting the reliability selection rationale. In cases of industrial facilities with unique design features, unique process hazards, or new technology, supplementing the evaluation with subjective probabilities by engineers and knowledge experts may be the best approach for judging performance reliability. Vick[25] provides detailed discussion on the use of subjective engineering judgment.

Step 4: Evaluate Target Vulnerability

FPS-LOPA can be used to evaluate multiple targets including people, property, and production downtime (business interruption). The primary target in most FPS-LOPA evaluations is the potential exposure vulnerability to people in terms of the probability of serious injury or fatality from the postulated FPS-LOPA scenario. This evaluation mainly relates to emergency response actions. For example, for a given fire scenario that presents a life safety risk, the probability of occupant vulnerability is based on the population affected (i.e., people present at the time of the potential incident), evacuation or life

Table 5-13.9 ***Relating Performance Measures to Performance Success Probability (solely for example purposes)***

Performance Measures	Performance Integrity Level (PIL) Rating	Performance Failure on Demand (P_{fod}) Range	Performance Success Probability Range
• Design standards, minor to major deviations • Low–medium PIM quality score • Below average IMT program	PIL-1	>0.20	<0.80
• Design standards, no major deviations, only minor • Medium PIM quality score • Average IMT program	PIL-2	0.10–0.20	0.80–0.89
• Design standards, compliance met • High PIM quality score • Above average IMT program	PIL-3	0.10–0.05	0.90–0.95
• Design standards, exceed compliance requirements • Very high PIM quality score • Excellent quality IMT program	PIL-4	0.05–0.01	0.96–0.99

safety egress capability beyond the fire scenario exposure boundaries, egress response time, sheltering capabilities, and so on.

Vulnerability assessment requires an understanding of the manner in which the physically described quantities and types of fire effects (e.g., thermal exposure, combustion products, and overpressure) combine with characteristics of the target (e.g., exposed people, exposed property) to produce a particular level of impact. Unusual vulnerabilities of occupants (e.g., operators must shut down equipment before exiting), high number or density of occupants, unusual vulnerability of property (e.g., clean rooms), vulnerability to escalation (e.g., chemical releases, radiological release, collapse of structure, etc.) must also be considered.[17]

The probability of fatal injury to a person, within the boundaries of the exposure zone, is evaluated as an enabling event within the cause-consequence scenario. The base equation is the product of the frequency (*F*) of people present and the probability (*P*) that the people are vulnerable (i.e., susceptible to the effects of the fire or explosion). The vulnerability component may have multiple subfactors such as the notification system reliability, effectiveness of evacuation routes, sheltering facilities, time-related human response reliability, and so on.

$$\text{Likelihood}_{\text{fatal injury}} = F_{\text{people present}} \times P_{\text{vulnerability}}$$

The presence of humans in the exposure zone raises the level of risk. If people are present 100 percent of the time, then the risk will be much higher than if people are present in the area 1 percent of the time. The frequency of people present can "normally" be derived from plant records and interviews with operations and maintenance managers. However, many incidents occur under nonnormal situations such as when maintenance workers or contractors are working in an area performing nonroutine maintenance, testing, or emergency repairs.

The objective of planned evasive action is to reduce the potential consequences to people from fire or explosion incidents and, thus, is a mitigation factor. Evasive actions can include sheltering-in-place, blast-resistant control rooms, escape to a designated safe shelter, or evacuation from a building, a process area, or the plant area. For assessing evacuation time effectiveness from a building, there are numerous factors to consider, such as the nature of the incident and its intensity level, the type of building, building construction, ventilation systems, fire or blast resistance integrity, type of occupants, populations, efficiency of egress routes, and frequency and quality of occupant training. For an existing facility, based on specific initiating event scenarios, these factors can be evaluated and evacuation drills can be conducted and timed. For proposed facility design for new construction or renovation projects, evacuation time effectiveness may have to be modeled. Building evacuation models are commonly termed *egress models* and are based on studies of peoples' movement within buildings.

Human performance reliability or actions in fires versus emergency response and evacuation time can be a complex evaluation. Other chapters in this handbook and *Guidelines for Evaluating Process Plant Buildings*[26] and *Engineering Guide*[27] provide further information on this subject area.

Step 5: Estimate Scenario Risk

The likelihood of realizing a specific cause-consequence scenario is calculated using the general equation format

$$\text{Likelihood}_{\text{consequence}} = \text{Frequency (initiating failure event)} \times \text{Probability of ignition (enabling event)} \times \Pi\ \text{IFPL}\ P_{\text{fod}}\ \text{(probability of failure on demand of IFPLs)} \times \text{Probability of target vulnerability (enabling event)}$$

Each of these items has been addressed in previous sections of this chapter. The enabling events in this general equation include ignition and target vulnerability. Additional enabling events may be needed to realize the consequences associated with a specifically defined scenario.

Having a consistent format in which to perform FPS-LOPA risk calculations and providing the appropriate level of documentation are very important parts of the evaluation. The general process is illustrated in the FPS-LOPA example included in this chapter.

Step 6: Conduct Risk Tolerance Comparison

In this step, the calculated risk is compared to the risk tolerance criteria established by the plant and/or company. For FPS-LOPA evaluations at industrial facilities, the term *risk tolerance criteria* is normally used instead of acceptable risk limits. *Risk tolerance* infers an internal guideline that establishes risk threshold guidelines on fire and explosion incidents in terms of affecting life safety, company stability, and profitability. Risk criteria establish the types of risks and risk levels a company will tolerate for existing, new, or proposed processes, facilities, and plant operations.

Sources used to assist in the development of risk tolerance criteria include both human-caused and natural hazard accident statistics. The elements of acceptable risk, risk tolerance, risk perception, and so on are beyond the scope of this chapter. Barry[1] and Barry and Johnson[28] provide additional information on this subject.

For a project that involved the processing of combustible liquids, company management authorized a risk-based evaluation and established life safety and property risk tolerance criteria. Examples of the established fire risk tolerance criteria are presented in Tables 5-13.10 and 5-13.11 (for example purposes only). Table 5-13.10 presents an example of risk tolerance limits for life safety exposure levels. Table 5-13.11 presents an example of risk tolerance limits for property damage impacts from fire.

Step 7: Make Decisions on Risk Reduction

FPS-LOPA can provide the following information for a scenario on a consistent basis:[13]

- Worst-case unmitigated risk (assuming all fire protection layers fail)

Table 5-13.10 ***Life Safety Exposure Categories for ABC Complex***

Life Safety Exposure	General Definition	Likelihood Tolerance Limits (events/year)
1—Low	First aid (minor injury associated with firefighting or evacuation)	0.100
2—Moderate	Single-person injury requiring hospital treatment	0.010
3—Heavy	Multiple-person injuries requiring hospital treatment	0.001
4—High	Life-threatening injury or death on-site	1×10^{-5}
5—Major	Life-threatening injury/rad exposure or death off-site	1×10^{-6}

- As-is mitigated risk (with existing or proposed fire protection layers in place)
- Fire protection layer improvements necessary to reach a tolerable risk threshold

If risk tolerance criteria are not met, the following can be further evaluated:

1. Existing (or proposed) IFPLs need improvement (e.g., increased performance reliability)
2. More independent fire protection layers are needed
3. A combination of both may be needed

The foregoing three items are usually evaluated by the risk assessment team by listing fire protection system options and examining each alternative in terms of independence, effectiveness (to meet risk tolerance criteria), initial and annual costs, and the ability to audit the measure. The FPS-LOPA example included in this chapter illustrates the general process.

Step 8: Monitor the Risk

The effectiveness and independence of an IFPL must be auditable. The audit process confirms that the IFPL design, installation, and functional testing and maintenance systems are in place to achieve the specified performance reliability for the IFPL.[14]

The plant must adopt a zero tolerance toward IFPL inspection, maintenance, and testing (IMT) deviations and enforcement of administrative IFPLs. Any deviation without prior approval should be considered a serious deficiency on internal audits, as it can significantly modify the risk.

A management of change (MOC) program must also be implemented to address changes in occupancy, process operations, facility modifications, and so on, as these changes may substantially affect the performance reliability of IFPLs and, thus, affect the risk level. An impairment program must be in place to address the level of contingency (temporary protection equivalent to the IFPL being taken out of service) needed for an impaired IFPL. If an IFPL is taken out of service for a planned or emergency impairment, the risk level will be affected. A continuous, high-quality, risk monitoring program is crucial for performance-based and risk-based fire protection design approaches.

Simple Example to Illustrate FPS-LOPA Steps

For the purpose of illustrating the steps involved in FPS-LOPA, a simple example related to a chemical process facility will be used. Plant X, utility area ABC, contains chemical pipe racks, cable trays, solvent pumps, and steam and cooling water lines for supplying process facilities A, B, and C. A fire in this area could expose operators and maintenance staff to fire and toxic chemicals and could potentially shut down production in all three process areas.

As discussed at the beginning of this chapter, the type of risk-informed evaluation and level of detail should depend on the complexity of the risk and the needs of the decision maker. Plant management realizes the importance of the utility area in the operation of process areas A, B, and C and the potential exposure it could present to workers.

Due to the uncertainty involving the potential likelihood of a major fire event, concerns about the

Table 5-13.11 ***Property Damage Impact Categories for ABC Complex***

Property Damage Levels	Damage Factor Range (%)	General Definition	Likelihood Tolerance Limits (events/year)
1—Slight	0–1	Limited localized minor damage not requiring repair	0.1
2—Light	1–10	Significant localized damage of some components generally not requiring major repair	1×10^{-3}
3—Moderate	10–25	Significant localized damage of many components warranting repair	1×10^{-4}
4—Heavy	25–60	Extensive process equipment damage requiring major repairs	1×10^{-5}
5—Major	60–100	Major widespread damage that may result in major structural damage	1×10^{-6}

Table 5-13.12 ***Example of FPS-LOPA Scenario Components***

Fire Hazard	Initating Event(s)[a]	Enabling Event(s)[b]	Expected Consequence(s)[c]	Prevention Controls[d]	Mitigation Measures[d]
Combustible solvent	Mechanical failure—pump seal failure releases solvent into utility area	1. Ignition of the solvent creates a pool fire 2. Operators and maintenance staff are present in the area for instrumentation checks, sampling, safety checks, equipment maintenance, and testing	Potential for major fire, which exposes chemical lines and could expose operators or maintenance staff in the area to fire and toxic chemicals	Pump design—double mechanical seals Pump mechanical integrity program Combustible control program to keep combustibles away from equipment	Dike around pump Ceiling-level sprinkler system Trained plant fire brigade

Assumptions:

[a]Extracted from hazard evaluation, what-if analysis

[b]Based on site-specific survey, ignition source identification and mapping, and interviews with operators and maintenance staff

[c]Fire modeling was conducted as part of consequence analysis

[d]Existing controls and measures

performance reliability of the existing fire protection in this area, and various past opinions regarding fire protection improvements, plant management has identified this as a Class B decision (see Table 5-13.1) and has requested an FPS-LOPA evaluation. The following summarizes the steps conducted by the FPS-LOPA team, which consists of representatives from engineering, operations, maintenance, safety, environmental, and fire protection.

Step 1: Develop Accident Scenarios

Table 5-13.12 provides a summary of FPS-LOPA components related to the specific scenario involving a combustible solvent pool fire, exposing overhead chemical lines and operations and maintenance personnel. It was assumed that, based on hazard evaluation, consequence analysis, and risk screening, this scenario provides an upper-bound credible scenario in terms of people exposure. In addition, it provides a primary design-basis scenario for evaluating the performance reliability of existing fire protection systems in this area.

Step 2: Determine Initiating Fire Event Likelihood

Table 5-13.13 provides a summary of FPS-LOPA initiating fire event likelihood. The lower-bound failure rate for pump seal failures from Table 5-13.6, "Example of Some Initiating Event Frequency Ranges," was used in this example based on the engineering evaluation of the prevention features.

Information on prevention controls is generally used in an FPS-LOPA analysis to choose between an upper or lower bound for initiating event failure frequency. In this example pump design includes a double mechanical seal making it less prone to leakage. The pump is used in a relatively low-pressure, low-flow-rate application. The pump is part of the plant's mechanical integrity program so it receives scheduled IMT (inspection, maintenance, and testing). The plant has a combustible control program,

Table 5-13.13 ***Continuing Example, FPS-LOPA Initiating Fire Event Likelihood***

Scenario Number	Initiating Event	Enabling Event—Ignition	Initiating Failure Event Frequency	Enabling Event—Ignition Event Probability*	Initiating Fire Likelihood (fires/year)
SN-01	Mechanical failure—pump seal failure releases solvent into utility area ABC	Ignition of solvent creates a pool fire scenario	0.03 failures/year Note: There are three solvent pumps Reference Table 5-13.6 for pump seal failure, lists a lower-bound failure frequency of 0.01 failures/pump-year	0.60 Engineering judgment*	0.018 fires/year

*Enabling event—ignition event probability; engineering judgment based on hazard evaluation, site-specific inspection, interviews with plant operators and maintenance staff. Ignition sources in area identified in terms of availability, ignition source locations mapped, and ignition source strengths evaluated in relationship to the initiating event scenario(s).

so it receives scheduled IMT (inspection, maintenance, and testing). The plant has a combustible control program, which involves monthly self-inspections and quarterly audits, and includes limiting and maintaining transient combustibles in the utility area so a transient combustible fire will not cause failure in utility area equipment such as the solvent pump system.

The solvent pool fire bounds an electrical fire, transient combustible fire, electric forklift fire in terms of the risk of exposure to the chemical pipe rack and to people in the area at the time of a potential incident. Therefore, it represents a credible design-basis fire scenario in which to evaluate the performance reliability of fire protection mitigation measures in meeting the established risk tolerance criteria.

Step 3: Assess Performance Reliability of Independent Fire Protection Layers (IFPLs)

Fire protection evaluation boundaries are the utility area, which is cut off from the adjacent process areas A, B, and C by 2.0-hour fire-rated walls and 1.5-hour fire-rated doors. Since the fire scenario being evaluated is exposure within the utility area to operators, maintenance staff, and chemical pipes, the performance of the fire walls is not directly evaluated within this example FPS-LOPA. However, because of the fire barrier importance in confining the fire to the utility area, it could be further reviewed in a supplemental fire wall performance reliability analysis to validate the selection of the fire evaluation boundaries.

The following provides a brief description of the fire protection mitigation measures listed in Table 5-13.12 in terms of their functional performance expectations or requirements.

Dike around solvent pump: The existing dike is 4.0 inches (10.16 cm) high and was initially designed to contain small solvent spills. At the existing solvent flow rate, a seal failure or failure at a flanged inlet or outlet connection to the pump could result in a solvent release rate that could overflow the existing solvent dike within 2 to 3 minutes. The dike has not been credited as an IFPL.

Ceiling-level sprinkler system: This system is an automatic active mitigation measure. The original design intent was to provide for fire control and suppression of fires in the utility area. This design allowed the pipe rack, which contains a variety of process chemicals (some of which are highly corrosive and highly toxic), to be protected from excessive temperatures that could cause pipe failure and release of these materials. The existing system is designed for 0.40 gpm per ft^2 (16.3 L/min·m^2) over the most remote 2500 ft^2 (232 m^2).

Operation of the sprinkler system sounds an outside water motor gong alarm and transmits a water flow signal to a constantly attended control room, from which the plant's fire brigade is notified. There are obstructions to water spray distribution over the solvent pump equipment due to sprinklers being obstructed by overhead pipe runs and ventilation ducts. Some sprinkler heads are corroded; some IMT records are missing information and are not consistent.

For this example, we will assume the use of an engineering evaluation model approach (see Table 5-13.9) to assess the potential performance success of the existing sprinkler system. Based on identified minor design compliance deficiencies, medium PIM (performance integrity measure) score, and average IMT (inspection, maintenance, testing), a PIL-2 (performance integrity level) lower bound was selected, which is equivalent to a 0.20 P_{fod} (probability of failure on demand).

Plant fire brigade response: The plant fire brigade response performance can provide a minimum of five responders to this fire area in full turnout gear within 10 to 12 minutes. Based on evaluation of alarm notification time, resource availability analysis, and timed response drills, this capability can be provided 80 percent of the time. The public fire department response time is approximately 20 to 25 minutes.

Based on fire modeling, an uncontrolled solvent pool fire could initiate failure of chemical pipe lines and a severe people exposure within 5 to 10 minutes. Based on the response time constraints for this specific scenario neither the plant fire brigade nor the public fire department is credited as an IFPL.

Table 5-13.14 provides a summary of FPS-LOPA independent fire protection layers (IFPLs). Based on the specific solvent pool fire scenario and the time frame for target vulnerability, the only existing credible IFPL is ceiling-level automatic sprinkler protection.

Step 4: Evaluate Target Vulnerability

Vulnerability evaluation involves solvent fire exposure to overhead chemical pipes, which contain corrosive and toxic chemicals, and exposure to operators and maintenance staff from fire and released toxic chemicals.

Based on fire modeling, an uncontrolled solvent pool fire could initiate failure of chemical pipe lines and a severe people exposure within 5 to 10 minutes. The factor that enables the life safety exposure likelihood is the probability of having operators or maintenance staff present in the utility area at the time of a potential solvent pool fire incident and the probability of severe or fatal injury vulnerability.

$$\text{Likelihood}_{\text{fatal injury}} = \text{Probability}_{\text{people present}} \times \text{Probability}_{\text{life safety vulnerability}}$$

The probability of having people in this area can generally be estimated from interviews with department supervisors. The probability of severe or fatal injury requires evaluation of the expected fire growth profile, smoke generation, and the domino effect from heated toxic chemicals being released into the area versus the time the fire is detected by the people in the area (either by sensing the situation or by alarm notification) and the time to exit the area.

Table 5-13.15 provides a summary of the life safety exposure likelihood evaluation for the solvent pool fire scenario.

Table 5-13.14 *Example FPS-LOPA—IPL Probability of Failure on Demand*

Independent Fire Protection Layers—IFPLs	Engineering-Based Performance Integrity Level (PIL)	Probability of FPS Performance Success Based on Functional Requirements	P_{fod} of IFPL (probability of failure on demand)	Remarks
Dike around solvent pump				Not being credited as an IFPL
Ceiling-level sprinkler system	PIL-2 Lower bound	0.80	0.20	Can be credited as an automatic IFPL; refer to Table 5-13.9
Plant fire brigade response				Not being credited as an IFPL
Fire barrier wall between utility area and process areas A, B, and C				Not directly relevant to the solvent pool fire scenario affecting chemical lines in the utility area or operators/maintenance staff present in the utility area

Table 5-13.15 *Example FPS-LOPA—Life Safety Exposure Likelihood*

Scenario	Consequences	Frequency of People in Area	Probability of Fatal Injury	Life Safety Exposure Likelihood
SN-01	Major fire that exposes chemical lines and could expose operators or maintenance staff in area to fire and toxic chemicals	Operators and maintenance staff are in the utility area approximately 4100 hours per year 4100 hr/8760 hr-yr = 0.47 1 to 3 people are in the utility area approximately 47% of the time. To be conservative, estimate people availability at 57% of time	This is the probability of fatal injury if a person is in area at the time of an uncontrolled solvent fire incident Based on deterministic modeling and engineering judgment of the rate of fire growth and toxic gas development versus evaluation of the time for personnel sensing of the fire or alarm notification and time to exit the area, a probability of 0.60 has been assigned	People availability (frequency) × Probability of fatal injury = 0.57 people present/year × 0.60 fatal injury potential = 0.34 To be conservative, round up to 0.40 as life safety exposure likelihood

Step 5: Estimate Scenario Risk

The general FPS-LOPA equation for estimating the likelihood for a specific cause-consequence scenario, such as the solvent pool fire scenario in this example, can be shown as

$$\begin{gathered}\text{Likelihood}_{\text{consequence}} = \\ \text{Frequency (initiating failure event)} \times \\ \text{Probability of ignition (enabling event)} \times \\ \Pi\ \text{IFPL}\ P_{\text{fod}}\ \text{(probability of} \\ \text{failure on demand of IFPLs)} \times \\ \text{Probability of target vulnerability} \\ \text{(enabling event)}\end{gathered}$$

Substituting the results from the example (from Tables 5-13.12 to 5-13.15)

$$\begin{gathered}\text{Likelihood}_{\text{consequence}} = 0.03\ \text{pump seal failures/year} \\ \times 0.60\ \text{ignition} \times 0.20\ P_{\text{fod}}\ \text{sprinkler system} \times 0.40\ \text{life} \\ \text{safety exposure} = 1.44 \times 10^{-3}\ \text{events/year}\end{gathered}$$

Normally a form or spreadsheet is used to document an FPS-LOPA scenario evaluation. Table 5-13.16 provides an example of a documentation format.

Step 6: Conduct Risk Tolerance Comparison

Based on Step 5, the existing risk is estimated at 1.44 $\times 10^{-3}$ events/year. The plant's risk tolerance criterion is 1.0×10^{-5} events/year (assumes a risk tolerance based on Table 5-13.10, "Example Life Safety Exposure Categories," for life-threatening injury or death on-site, established at 1.0×10^{-5} events/year). For this example, the estimated existing risk level exceeds the established risk tolerance level; therefore, additional IFPLs are needed (i.e., to reduce the existing risk level approximately two orders of magnitude).

Step 7: Make Decisions on Risk Reduction

The general approach for this step involves conducting an FPS-LOPA team brainstorming session, where various fire protection options and alternatives are discussed in terms of the risk reduction potential, feasibility, initial and annual costs, installation issues, process downtime during installation, and so on. For this example, it is assumed that relocating solvent pumps outside, rerouting chemical pipes, and constructing a fire-rated compartment around the solvent pumps are not feasible alternatives. It is further assumed that based on review of several

Table 5-13.16 ***Example FPS-LOPA—Documentation Table***

FPS-LOPA No: SN-01
Plant X: ABC Utility Area
Location: Bldg. 601- Utility Corridor

Process: Utility area ABC contains chemical pipe racks, cable trays, solvent pump, steam and cooling water lines for supplying process facilities A, B, C. A fire in this area would expose operators and maintenance staff to fire and toxic chemicals and could shut down production in all three process areas.

Scenario Source: Process hazard analysis (PHA) Item ABC-01; pump seal failure resulting in a solvent pool fire

Scenario: Mechanical failure of pump seal failure releases combustible solvent into utility area; ignition of the solvent creates a pool fire
Operators and maintenance staff are in area approximately 4100 hours per year, generally 1 to 3 people. Major fire would fail chemical lines and could expose operators or maintenance staff in area to fire and toxic chemicals.

Date:
Evaluation by:
Review by:
Area/Process
- ☒ Existing Design
- ❍ New Design
- ❍ Proposed Design Modifications

P&ID Nos. or Equipment IDs: 601-A, 602-B, 603-C
Risk Tolerance:
Maximum Target Likelihood: 1.0×10^{-5} events/year
Reference: Plant Risk Assessment Guideline RA02

Item	Description	Probability	Frequency
Initiating event likelihood: Solvent pump seal failure	Pump seal failure releases solvent into the utility area Note: There are three solvent pumps. Reference Table 5-13.6 for pump seal failure, lists a lower-bound failure frequency of 0.01 failures/pump-year		0.03 events/year
Enabling event likelihood: Ignition occurs	Ignition event probability; Engineering judgment based on hazard evaluation, site-specific inspection, and interviews with plant operators and maintenance staff. Ignition sources in area were identified in terms of availability and ignition source strengths in relationship to the initiating event scenario	0.6	
Likelihood of an Initiating Fire		P_{fod}	0.018 fires/year
IFPL Fire Protection Layers P_{fod}—probability of performance failure on demand	Ceiling-level sprinkler system activates, suppresses fire, and prevents failure of chemical lines with corrosive and toxic chemicals Based on engineering evaluation used a PIL-2 (performance integrity level) lower bound from Table 5-13.9	0.20	
Other safeguards not directly credited as independent protection layers	Dike around solvent pump Plant fire brigade (response time to this scenario not adequate)		
Likelihood of an Unmitigated Fire (uncontrolled fire)			3.6×10^{-3} uncontrolled fire events/year
Target vulnerability: Life safety exposure to operators/ maintenance people	Enabling event: Life safety exposure likelihood to operators/maintenance people Probability of fatal injury (see Table 5-13.15)	0.40	
Likelihood of Consequence Being Realized			1.44×10^{-3} events/year
Fire Risk Tolerance Established by Plant	**1×10^{-5} events per year;** maximum tolerable risk of a major fire that could cause extensive equipment damage; maximum tolerable risk of a fatal injury		Comment: Fire risk tolerance criteria are not met with existing IFPLs

different alternatives, the following fire protection measures are selected for further FPS-LOPA evaluation.

Install heat detection system and interlocks to minimize the size of a solvent release: Install a localized heat (fire) detection system for the three solvent pumps. Operation of the heat detection system would be interlocked to automatically close a safety shutoff valve on the solvent line outside the building and send an alarm to the control room. This detection and mitigation measure would reduce the potential size, intensity, and burning duration of a solvent fire and reduce the likelihood of overhead chemical line failure. This system would be designed for a minimum 0.95 performance reliability.

Make improvements to the existing automatic sprinkler system: Install radiant heat flame shields at the underside of the chemical pipe rack. Install sprinkler protection under flame shields and under the ventilation air-supply duct, which is over 4.0 ft (1.22 m) in width. This will provide improved water spray coverage in this area, especially over the solvent pump equipment. Interlock the activation of the sprinkler systems to automatically close isolation valves on the bulk chemical tanks and the solvent safety shutoff valve and activate local alarms. Replace the corroded sprinkler heads and inspect the rest. Improve the sprinkler system inspection, maintenance, and testing program.

For this example, we will again assume the use of an engineering evaluation model approach (see Table 5-13.9) to assess the potential performance success of the proposed sprinkler system improvements. Based on engineering evaluation and judgment, improvements would increase the PIL (performance integrity level) to an upper bound PIL-3 level, which is equivalent to a 0.05 P_{fod} (probability of failure on demand) or a 0.95 performance reliability.

Reduce life safety vulnerability by early-response fire alarm notification: Install two beam-type smoke detectors at the ceiling level. Operation of any one detector activates local alarms in the utility area, including strobe lights, as this area has moderate noise levels. Manual fire alarm pull boxes will be installed at both exterior exit doors and will be interlocked to automatically close isolation valves on the bulk chemical tanks and the solvent safety shut off valve. Operation of one detector, a manual fire alarm pull box, or sprinkler system will transmit a signal to a constantly attended control room and the plant fire brigade will be immediately dispatched.

Plant management realizes the importance of the utility area in the operation of process areas A, B, and C. The installation of beam smoke detectors also provides the capability for detection of potential electrical cable fires and faster response of the plant's fire brigade. The provision of automatic interlocks reduces the potential for a large solvent or toxic chemical release inside the utility area.

Table 5-13.17 illustrates spreadsheet-type documentation of the proposed risk reduction strategy. The proposed risk reduction measures reduce the solvent pool fire life safety exposure likelihood to 9.0×10^{-6} events/year, which meets the plant's established risk tolerance criteria.

Step 8: Monitor the Risk

As previously stated, the effectiveness and independence of an IFPL must be auditable. The audit process must confirm that the risk reduction system IFPL design, installation, and functional testing and maintenance systems are in place to achieve the specified performance reliability for the IFPL based on the FPS-LOPA risk reduction decision analysis.

Auditing, management of change (MOC), and impairment procedures will be established for the independent solvent heat detection system and interlocks, the ceiling-level automatic sprinkler protection system protecting the utility area, and the beam early-warning smoke detection system and alarms for improved independent people notification and evacuation time response (i.e., independent from the sprinkler system water flow local alarm). It is critical that these risk-monitoring measures are implemented to continuously maintain the risk tolerance criteria established by plant management.

Class C Decisions: Quantitative Risk Assessment (QRA)

FPS-LOPA goes beyond the typical use of a qualitative risk matrix but is less detailed than quantitative risk analysis (e.g., QRA used for Class C decisions).

Table 5-13.17 ***Example FPS-LOPA Risk Reduction Evaluation Spreadsheet***

	A	*B*	*C*	*D*	*E*	Likelihood
Design Phase	Initiating Failure Event	Enabling Event 1: Ignition	FPS-IPL 1 P_{fod}	FPS-IPL-2 P_{fod}	Enabling Event 2: Target Vulnerability	Fire Scenario Incident Likelihood
Existing design	0.03 Pump seal failure	0.60 Ignition of solvent release	0.20 Ceiling-level sprinkler protection		0.40 Life safety exposure 1–3 people	1.44×10^{-3} events/year
Proposed risk reduction design strategy	0.03 Pump seal failure	0.60 Ignition of solvent release	0.05 Install an independent heat detection system interlocked to shut down bulk chemical isolation valves and solvent safety shut off valve. Design for a minimum 0.95 performance reliability	0.05 Make improvements to the sprinkler system. Design for a minimum 0.95 performance reliability	0.20 Life safety exposure reduced 50% based on installation of beam smoke detectors and local alarms. Engineering evaluation and judgment	9.0×10^{-6} events/year

Note: Likelihood= $A \times B \times C \times D \times E$

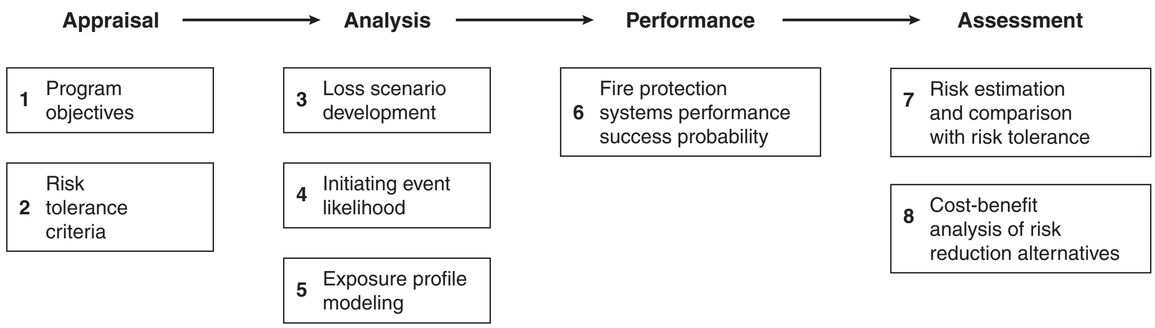

Figure 5-13.8. ***Risk-informed performance-based fire protection steps.***[1]

FPS-QRA methods provide a higher degree of detail and accuracy than FPS-LOPA. For example, in FPS-QRA, fault tree analysis is normally applied to assess the primary contributing factors associated with initiating fire events and fire protection system performance. Having a detailed breakdown of contributing risk factors and quantification of these factors allows more insight into options and alternatives to reduce the risk to a tolerable level in a cost-effective manner. Event tree analysis of multiple scenarios, use of input sensitivity analysis, use of probability distribution, and use of uncertainty analysis methods provide additional information on which more intelligent risk-based decisions can be made.[1,12]

Figure 5-13.8[1] presents an example of the steps to take in an FPS-QRA risk-informed, performance-based fire protection evaluation, which can be used to address Class C decisions when additional levels of analysis and detail are warranted. Risk-informed, performance-based assessments involve the quantification of initiating fire event likelihoods, development of exposure and consequence profiles (life safety, property, business interruption) using fire and explosion modeling and event tree analysis, evaluation of the performance success probability (i.e., performance reliability) of existing or proposed fire protection systems, comparison of risk results with risk tolerance criteria, and cost-benefit analysis of

Table 5-13.18 ***Brief Comparison Between FPS-LOPA and FPS-QRA Methods***

Item	FPS-LOPA	FPS-QRA
Decision Level (Note: Refer to Table 5-13.1.)	*Class B Decisions*	*Class C Decisions*
Accident scenario development	Evaluates a defined (normally bounding) cause-consequence pairing (typically identified during a qualitative hazard evaluation)	Can accommodate multiple cause-consequence scenarios using event tree analysis (ETA)
Initiating event frequency	Generally evaluates single component failure or single human error with a probability estimate for ignition Single point frequency estimate	Can assess multiple failures and contributing factors leading to a fire or explosion event, using fault tree analysis (FTA) Probability distributions can be applied within the ETA
Performance of independent fire protection system layers (IFPLs) Probability of performance failure	Generally applies an engineering judgment-based performance reliability estimate	Usually applies a performance success tree, which allows a more detailed evaluation of performance reliability in terms of • Design effectiveness • Availability • Operational reliability
Scenario risk estimation	Proves an order-of-magnitude estimate of the likelihood of realizing a specific cause-consequence scenario	Provides higher-accuracy risk estimates through application of FTA and ETA Can accommodate sensitivity and uncertainty analysis to improve confidence
Risk reduction analysis and decision analysis	FPS-LOPA takes a specific cause-consequence scenario, determines how many protection layers are provided by existing and/or recommended independent fire protection layers (IFPLS), and evaluates whether the number and performance reliability of IFPLs provide adequate risk mitigation to meet risk tolerance criteria	Goes beyond FPS-LOPA in terms of evaluating contributing risk factors through FTA and ETA, thus allowing better decisions to be made regarding risk reduction strategies Provides necessary information to conduct a credible cost-benefit economic analysis

risk reduction alternatives if risk tolerance limits are exceeded.

Table 5-13.18 provides a brief comparison between FPS-LOPA and FPS-QRA methods.

Summary

The use of an integrated or layered fire safety design approach (fire prevention, detection, passive and active protection levels, and emergency response) within a risk-informed framework provides both a balanced and quantitative method for addressing complex fire and explosion issues. It delivers supplemental decision-support information and alternatives, which allow engineers, risk managers, and regulators the capability to make cost-effective decisions based on the unique risk factors associated with a specific building, facility, or process.

The authority having jurisdiction (AHJ) is responsible for ensuring that the layers of independent fire protection needed are relative to the risk level and imposed risk tolerance criteria. However, it may be difficult to do without risk-based information that supports the level of fire safety achieved with the fire protection design strategy under review.

The use of risk-based computations, including quantification of the performance reliability of independent fire protection layers for scenarios with uncertainty factors or potentially moderate to high consequence levels, needs to be incorporated into performance-based fire protection design submittals if this supplemental information is requested by the AHJ.

The risk-informed evaluation approaches discussed in this chapter have been performed for numerous types of industrial processes, facilities, and operations. The techniques present many crossover application capabilities to examine design-based fire scenarios and risk levels at commercial buildings, high-rise buildings, hospitals and health care facilities, large assembly areas, and so on.

A robust performance-based fire safety design code cannot be achieved without practical guidelines for delivering supplemental risk-informed information either as a supplement to performance-based design submittals on a voluntary basis or as requested by the building code official or regulator.

Nomenclature

AHJ	authority having jurisdiction
ETA	event tree analysis
F	frequency
FHA	fire hazard analysis
FMEA	failure modes and effects analysis
FPS	fire protection system
FPS-LOPA	fire protection system-layer of protection analysis
FPS-QRA	fire protection system-quantitative risk assessment
FRE	fire risk evaluation
FTA	fault tree analysis
HAZOP	hazard and operability analysis
HRA	human reliability analysis
IFPL	independent fire protection layer
IMT	inspection, maintenance, testing
IPL	independent protection layer
LOPA	layer of protection analysis
MOC	management of change
NFPA	National Fire Protection Analysis
P	probability
P_{de}	probability of design effectiveness
P_{fod}	probability of failure on demand
PHA	process hazard analysis
PIL	performance integrity level
PIMs	performance integrity measures
PML	probable maximum loss
P_{or}	probability of operational reliability

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