Chapter 8

Cost/Benefit Analysis of Risk Reduction Alternatives

Chapter Contents

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COST/BENEFIT ANALYSIS OF RISK REDUCTION ALTERNATIVES

8

8.1 INTRODUCTION

This chapter addresses the cost/benefit analysis of risk reduction alternatives, which is Step 8 in the risk-informed, performance-based, decision making process (see Fig. 8.1). The term "risk reduction" in this chapter is defined as the application of technological and administrative measures to reduce fire or explosion risk to a tolerable level. This chapter does not consider risk transfer via insurance.

Reduced fire risks can mean fewer fire losses and claims, a more efficient operation, better employee morale, higher profits, better public relations, and greater investor confidence. However, this reduced risk is not obtained without cost. Decision makers must recognize and quantify fire risks and assess cost-effective approaches for reducing them. This is done by conducting cost/benefit analysis for selected risk reduction strategies.

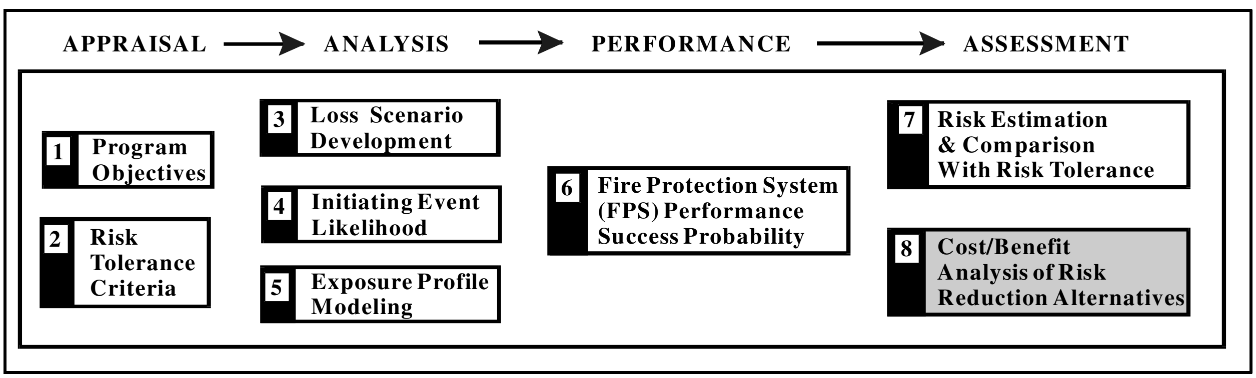
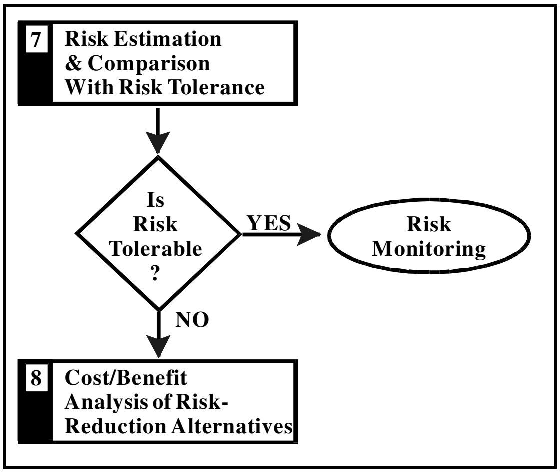


Fig. 8.1: Risk-Informed, Performance-Based Fire Protection Steps

In Step 7, Risk Estimation and Comparison with Risk Tolerance, the risk was quantified and compared to the risk tolerance criteria. As depicted in Fig. 8.2, if the existing risk level is not tolerable, then proceed to Step 8. If risk is tolerable at that point, then a risk monitoring program should be implemented. Risk monitoring is discussed in Sect. 8.7.

Fig. 8.2: Risk Assessment Steps Leading to Cost/Benefit Analysis

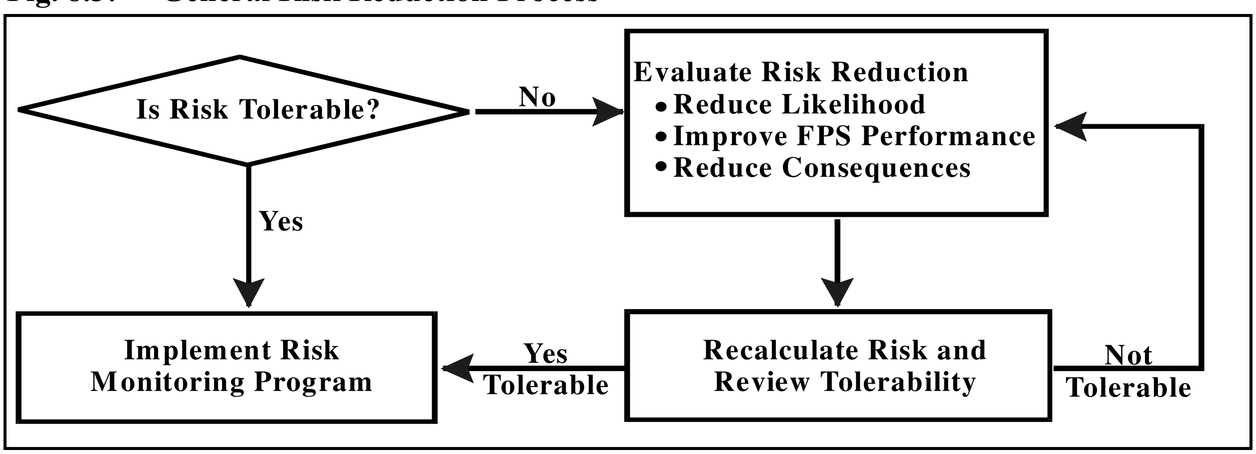


As presented in Fig. 8.3 there are three primary ways to reduce fire and explosion (F&E) risk:

- Reduce the initiating event likelihood.
- Improve FPS performance.
- Reduce the consequence levels.

The final risk management strategy will likely include a combination of these measures to optimize the cost/benefit. Each of these risk reduction measures is addressed in this chapter.

Fig. 8.3: General Risk Reduction Process



Weak links and Brain-Storming

In most fire-risk-based projects, completion of Steps 3 through 7 (Fig. 8.1) leads to the initial identification of the "weak links" that contribute to the existing risk level in the system under review.

For example, Fig. 8.4 indicates that the existing annualized risk far exceeds the established risk tolerance criteria, making risk reduction necessary. But why? What are the weak links?

These initial questions are answered by examining the event tree model developed during the risk-based evaluation. From review of the example event tree in Fig. 8.5, one could observe:

① The initiating event likelihood appears high; 0.33 fires/year equates to a potential of having a fire every three years.

② The probability of detection system success is low, estimated at 0.65. This indicates a probability of only 6.5 out of 10 times that the initiating fire scenario will be detected within 1 – 3 min (refer to time line in Fig. 8.5).

③ If the emergency control system (ECS) is not successful (i.e., shutdown of a flammable liquid pump), then the probability of automatic fire suppression within 5 – 10 min is low.

④ The performance-success probabilities of the ECS and automatic suppression system may not meet the FPS performance criteria established by the company.

⑤ There are some high life safety exposure levels associated with undetected, uncontrolled fire potentials (i.e., branch lines 9 and 12).

.Fig. 8.4: Example of Existing Annualized Risk Versus Risk Tolerance

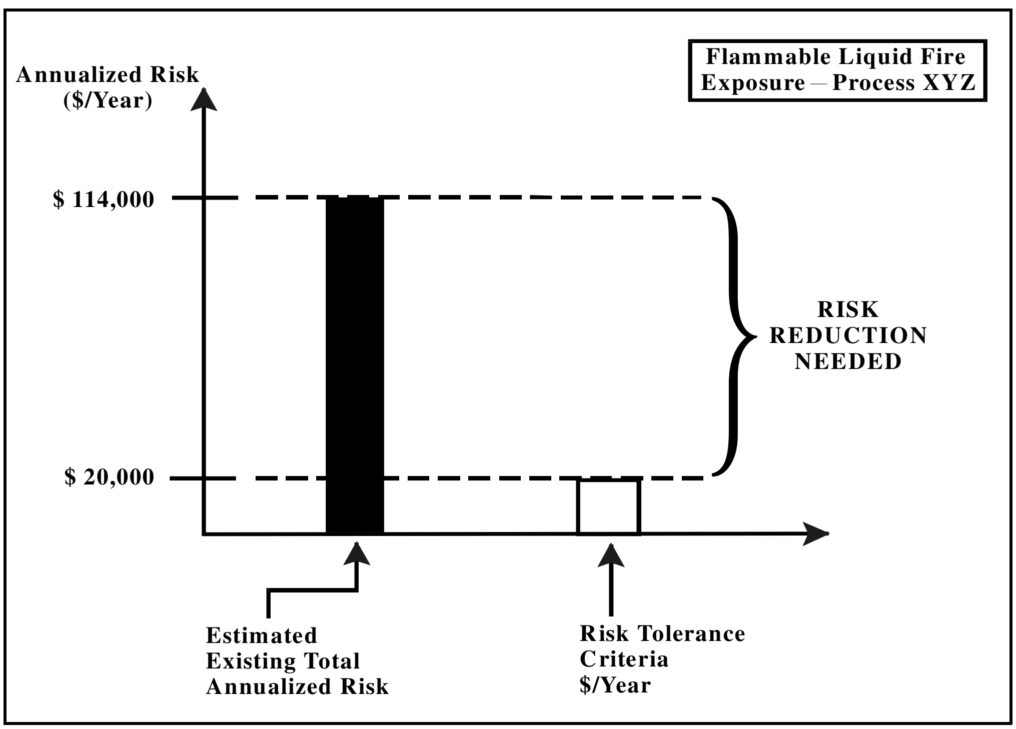
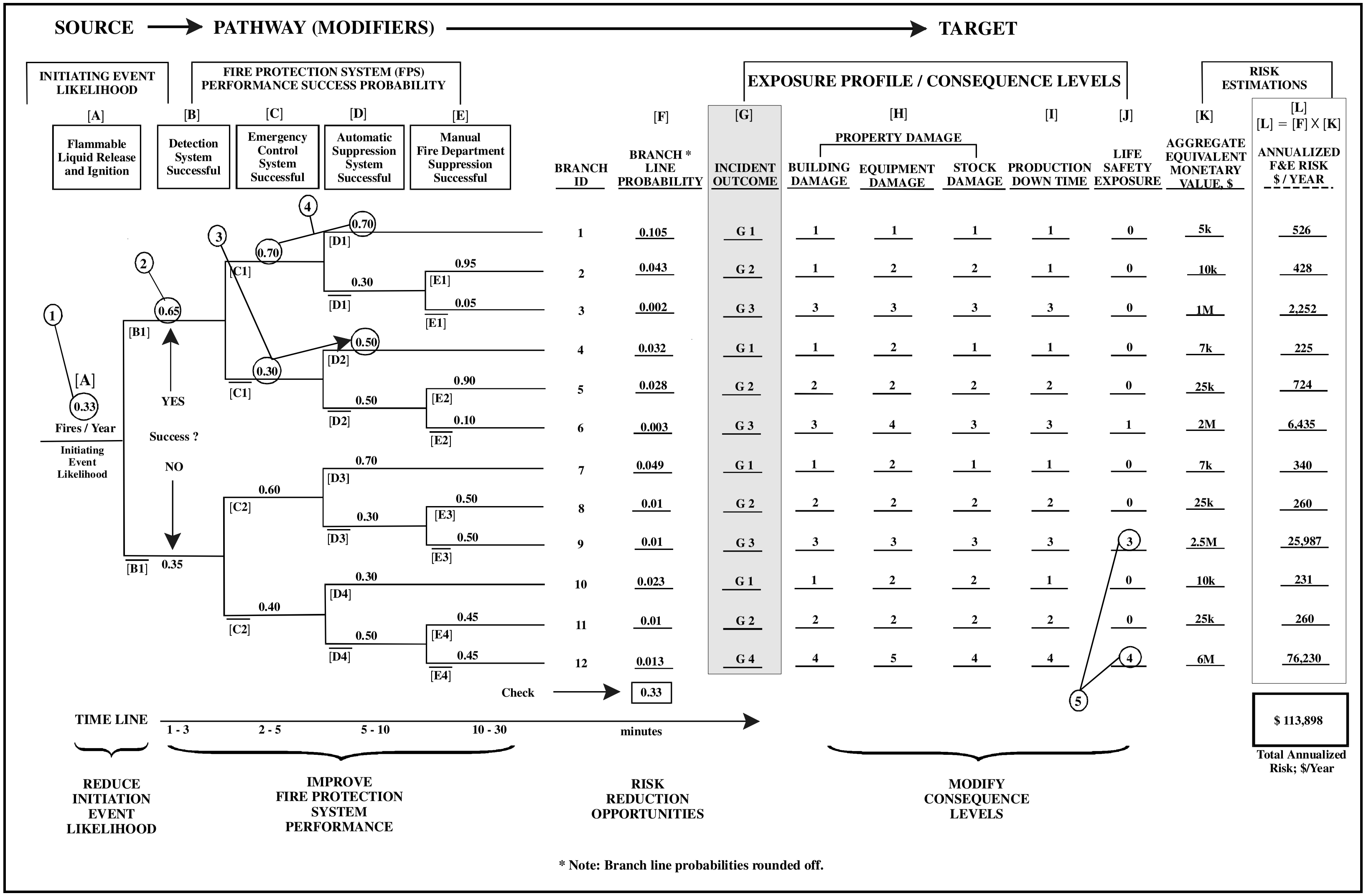


Fig. 8.5: Example Event Tree Fire Risk Model



BRANCH ID	[F] BRANCH * LINE PROBABILITY	[G] INCIDENT OUTCOME	[H] PROPERTY DAMAGE: BUILDING DAMAGE	[H] PROPERTY DAMAGE: EQUIPMENT DAMAGE	[H] PROPERTY DAMAGE: STOCK DAMAGE	[I] PRODUCTION DOWN TIME	[J] LIFE SAFETY EXPOSURE	[K] AGGREGATE EQUIVALENT MONETARY VALUE, $	[L] [L] = [F] X [K] ANNUALIZED F&E RISK $ / YEAR
1	0.105	G 1	1	1	1	1	0	5k	526
2	0.043	G 2	1	2	2	1	0	10k	428
3	0.002	G 3	3	3	3	3	0	1M	2,252
4	0.032	G 1	1	2	1	1	0	7k	225
5	0.028	G 2	2	2	2	2	0	25k	724
6	0.003	G 3	3	4	3	3	1	2M	6,435
7	0.049	G 1	1	2	1	1	0	7k	340
8	0.01	G 2	2	2	2	2	0	25k	260
9	0.01	G 3	3	3	3	3	3	2.5M	25,987
10	0.023	G 1	1	2	2	1	0	10k	231
11	0.01	G 2	2	2	2	2	0	25k	260
12	0.013	G 4	4	5	4	4	4	6M	76,230

* Note: Branch line probabilities rounded off.

As part of the event tree "weak-link" review, a brain-storming session is usually conducted with the risk assessment team and decision makers to:

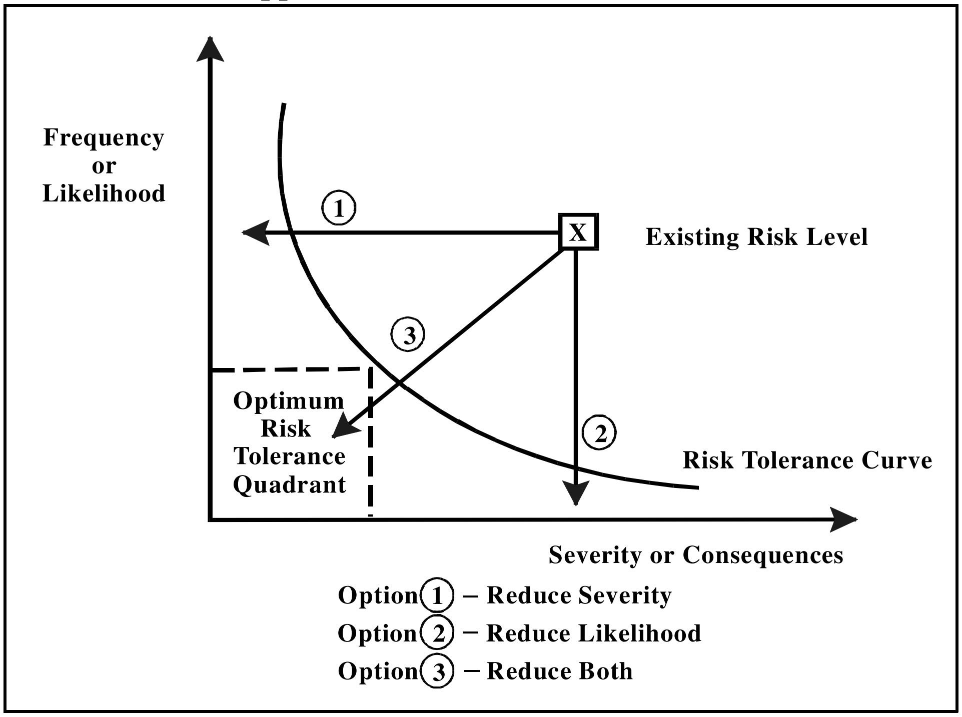
- *Develop a preliminary list of risk reduction alternatives*. The team systematically considers alternative responses to reduce the risk of each scenario. Responses are considered that eliminate, prevent, mitigate, and respond to potential risks. A table can be used as a checklist to ensure that a range of alternatives are identified.
- *Screen and eliminate the least-feasible responses*. The list of alternative responses developed in the preceding step is then reviewed. Responses that are not feasible due to cost or other constraints are eliminated. An example format is presented in Table 8.1.

Table 8.1: Example Format for the Initial Listing and Screening of Risk Reduction Alternatives

EVENTS	EVENT FACTORS	LIST OF RISK REDUCTION ALTERNATIVES	FEASIBLE RISK REDUCTION ITEMS
Initiating fire events	Likelihood Modification: • Abnormal failure situations that provide fuel available for combustion (i.e., equip-ment failure, human error, external failures) • Oxygen availability • Ignition sources	[IDENTIFICATION] ↓	[SCREENING] ↓
Fire protection systems (FPSs)	FPS improvements: • Detection systems • Emergency control systems • Automatic suppression systems • Propagation limiting measures (i.e., fire barriers) • Manual loss control intervention		
Consequences, exposure at the target	Consequence modification: • Modify source fire heat-release rate • Modify life safety exposure levels • Modify production downtime exposure levels		

Conducting a brain-storming session encourages decision makers to collaborate with team members with different specialties. This interaction can result in some innovative ideas, but it can also initiate conflicts. For example, as illustrated in Fig. 8.6, some team members may focus on severity reduction via more or better "protection" features (1); some members may focus on "prevention" features to reduce the likelihood (2). The optimal path of negotiation is to pursue risk reduction strategies that reduce both severity and likelihood to a tolerable level (3).

Fig. 8.6: Risk Reduction Approaches



8.2 REDUCING INITIATING EVENT LIKELIHOOD

Methods for quantifying initiating fire events were described in Chap. 4. When evaluating alternatives for reducing initiating event likelihood, the critical decision that the risk assessment team and decision makers usually face is where to invest the limited resources available for improvements. The Pareto principle, or 80/20 rule, can generally be applied as a first step in this process. Typically 80–90% of the calculated top event likelihood is related to 10–20% of the contributing factors. These factors are termed the major, or dominant, contributing factors and are the items the risk assessment team should initially focus on.

The starting point for identifying contributing factors is an understanding of the general fault tree logic for evaluating initiating fire event likelihood, which was described in Chap. 4. As indicated in Chap. 4, even if the risk assessment team is applying historical data, recognizing the contributing factors related to these data are imperative.

Figure 8.7 provides a refresher of the general fault tree structure for initiating fire events from Chap. 4. As illustrated in this figure, the evaluation requires definition of a specific scenario for the top event. Using this fault tree logic as a general framework for reducing initiating event likelihood, one can begin to access the feasibility of the following alternatives:

1.0 Reduce the potential for combustible fuel being vulnerable to ignition. If combustible material is present as a normal part of operations (i.e., storage of combustible inventory in a production area), then the focus should be on minimizing ignition potential. If the fuel is normally contained (i.e., flammable liquids in pipes or tanks), then the reduction of abnormal failure events (equipment failures, human error, external failures) should be addressed and if applicable, the reduction of the failure potential by pre-fire mitigation features (instrumentation, shutdown, isolation, etc.) should be evaluated.

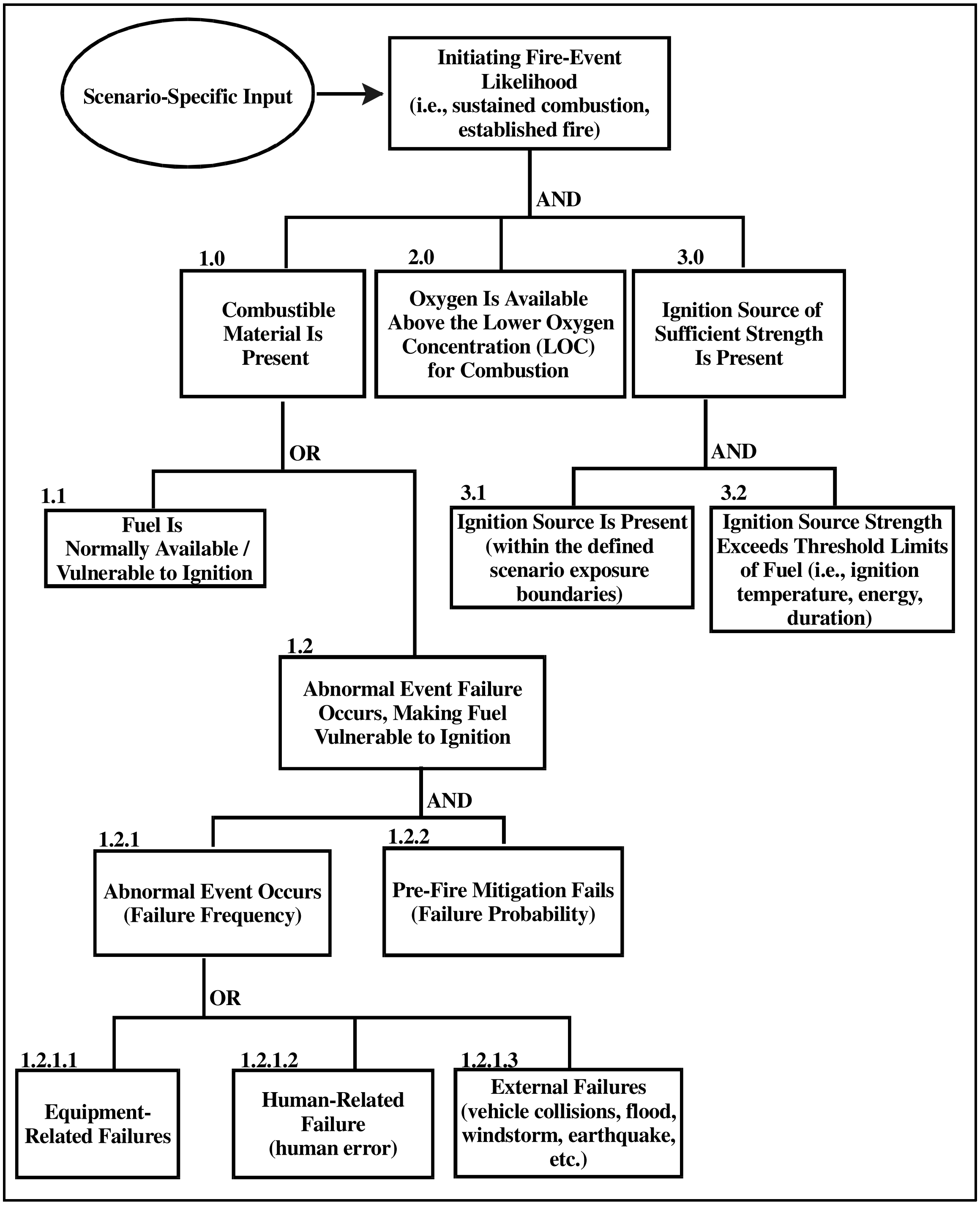
2.0 Reduce oxygen availability below the lower oxygen concentration (LOC) of the fuel. In outside open areas or inside large industrial buildings, there is sufficient oxygen to support initial combustion, and therefore the probability of oxygen availability is usually 1.0. In many industrial processes that involve handling flammable liquids and gases, oxygen reduction to prevent fires or explosions is provided by the addition of an inert gas such as nitrogen, carbon dioxide, or argon into an enclosed area (process vessel, tank, oven, room enclosure, etc.) Design techniques for reducing and limiting oxygen concentration below LOC can be considered for applications where a mixture of oxygen and flammable material is contained in an enclosure where the oxygen concentration can be controlled. The probability of exceeding LOC then becomes dependant on the failure probability of the oxidant reduction method and system.

3.0 Reduce the probability of ignition. Two primary factors are normally involved for ignition:

1. An ignition source must be present (within the defined scenario exposure boundaries)
2. The ignition source strength must exceed the threshold limits of the fuel (i.e., ignition temperature, energy, duration)

The first and most important part of evaluating ignition potential is to identify all potential ignition sources (fixed and temporary) and estimate the frequency of time the ignition source(s) are present. For those ignition sources that exceed the threshold ignition limits of the fuel, ignition source elimination or controls can be examined.

Fig. 8.7: General Fault Tree Logic for Initiating Fire Events



8.2.1 Evaluating Likelihood Reduction

The following steps can generally be followed when evaluating likelihood reduction:

1. Examine the percent contribution of major failure factors and rank them for further evaluation.
2. Evaluate the feasibility of likelihood reduction options.
3. Quantify selected likelihood reduction options.
4. Review risk tolerance criteria and recognize uncertainty issues.

To demonstrate these steps, a simplified example will be presented. Fig. 8.8 presents an initiating event fault tree structure for a flammable liquid fire scenario. Frequency and probability numbers have been added for example purposes.

Fig. 8.8: Simplified Example Estimating Existing Fire Event Likelihood

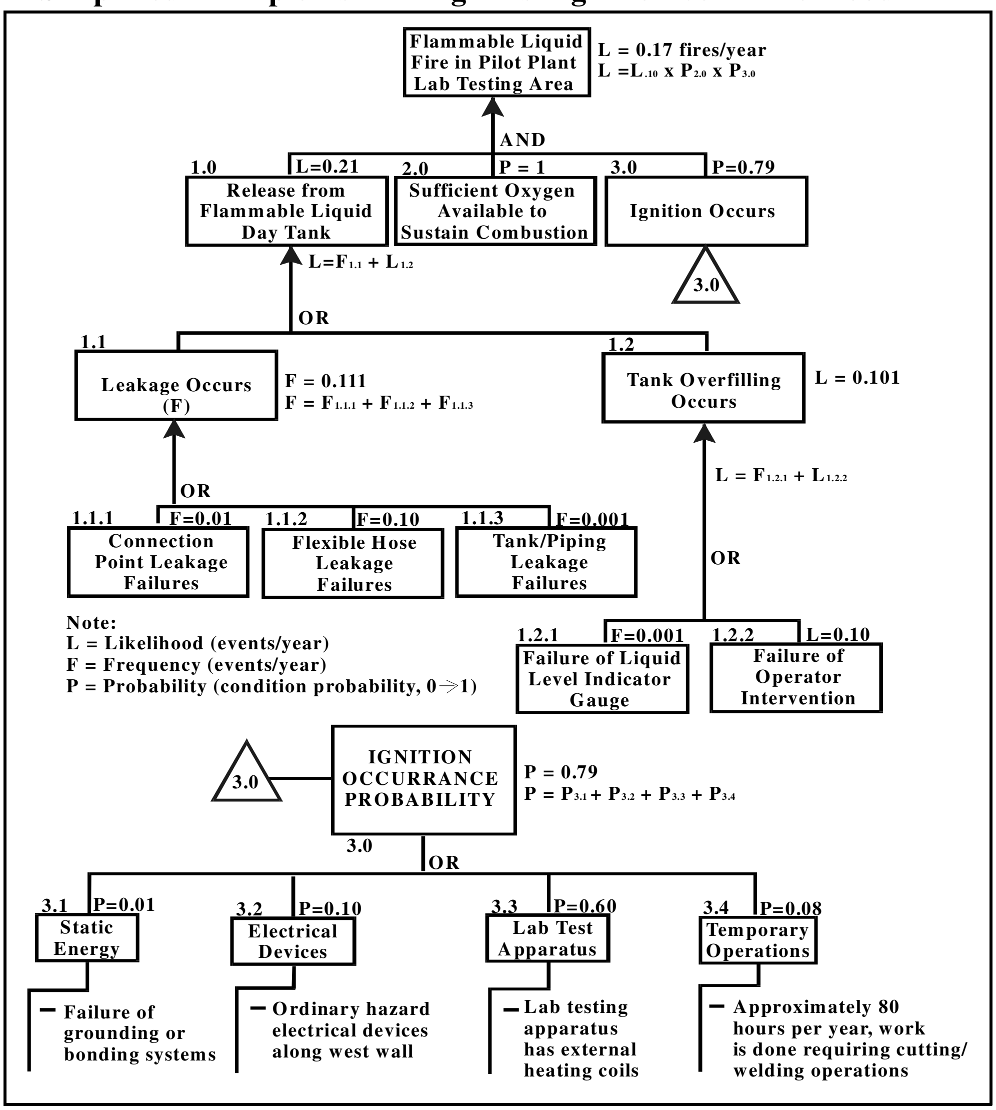


Table 8.2 provides a percent breakdown and ranking of major contributing failure factors as related to the example fault tree in Fig. 8.8. The percent contribution in Table 8.2 is for the designated failure mode event in the first column.

Table 8.2: Percent Contribution to Failure Mode for Fig. 8.8

FAILURE MODE EVENT	CONTRIBUTING FACTORS	PERCENT CONTRIBUTION TO THE FAILURE MODE	RANKING	REMARKS
1.1 Leakage	1.1.1 Connection point failures 1.1.2 Flexible hose failures 1.1.3 Tank/piping failures	9% 90% 1%	2 1 3	Flexible hose failure most dominant
1.2 Tank Overfilling	1.2.1 Instrumentation failure – level 1.2.2 Human error – operator intervention	1% 99%	2 1	Human error most dominant
3.0 Ignition	3.1 Static energy 3.2 Electrical devices 3.3 Lab test apparatus 3.4 Temporary operation – human error	1% 13% 76% 10%	4 2 1 3	Lab test apparatus and existing electrical devices most dominant failure potentials
Note: Numbers in columns 1 and 2 refer to Fig. 8.8				

The simple fault tree structure in Fig. 8.8, which can be calculated by hand or in a spreadsheet, allows for gate-to-gate estimation of percent contribution to intermediate event failure modes or to the top event in the fault tree. More detailed fault trees, which are usually analyzed with a computer program, would provide cut-set and importance analysis.

8.2.2 Evaluate the Feasibility of Likelihood Reduction Options

Table 8.3 presents an example format for screening fire event likelihood-modification options.

Table 8.3: Screening Fire Event Likelihood Modification Options

OBJECTIVE	MODIFICATION OPTIONS	FEASIBILITY SCREENING
(1.1) Reduce leakage frequency	• Eliminate flexible hoses, replace with fixed piping • Modify flexible hose failure potential by improving IMT (inspection, maintenance, testing) • Provide an enclosure around the day tank and flexible connections	– Not feasible based on design and seismic requirements – Feasible – Cost prohibitive
(1.2) Reduce tank overfilling likelihood	• Install a second high-level gauge with alarm • Improve operator training and procedures • Install an interlock for automatic pump shutdown following a high-level alarm	– Feasible – Operator has many duties. Cost-prohibitive to provide a second operator. Even with further improvements in training and procedure, uncertainty would still exist – Feasible
(3.0) Reduce ignition probability	• Replace existing lab apparatus with equipment classified as intrinsically safe • Eliminate ordinary electrical devices or replace with classified electrical devices • Eliminate temporary maintenance and hot work	– Feasible, will have to investigate equipment availability and costs – Feasible to replace with classified electrical – Not feasible for a pilot plant operation
Note: Numbers in column 1 refer to Fig. 8.8		

Quantification of selected likelihood reduction options is performed by using the methods and techniques described in Chap. 4, Initiating Event Likelihood. This section will provide a refresher of this information as applied to our example.

Flexible Hose Failure

Assume that the existing flexible hose failure rate (event 1.1.2 in Fig. 8.8) is represented in the upper failure range based on a PIM (Performance Integrity Measure) Quality Scoring evaluation (described in Chap. 4). An example PIM evaluation is provided in Table 8.4. As noted, the quality grades for PIM-4, Inspection/Maintenance Programs, and PIM-5, Testing Program, are rated D, very poor.

Table 8.4: Example PIM Quality Scoring Sheet

SYSTEM 008: Pilot-Plant Flammable-Liquid Day-Tank System

Performance Integrity Measures (PIM)		SUBSYSTEMS: / PIM INDICATORS	Flexible Hoses Grade	Flexible Hoses IMP	Piping Grade	Piping IMP	Pumps Grade	Pumps IMP	Tank Grade	Tank IMP
PIM-1 General Design Standards	A B C D F	Designed per Standard XX, Current Edition Designed per Standard XX, Older Edition Minor deviations from Standard Major deviations from Standard Not designed per Standard	B	3	B	4	A	4	A	4
PIM-2 Life-Cycle (Age)	A B C D F	Newer Equipment, Formally Acceptance Tested Newer, Not Formally Accepted Tested At or Slightly Below ½ Useful Life Above ½ Useful Life At End of Useful Life	B	3	A	3	A	4	A	4
PIM-3 Management of Change Program	A B C D F	Very Good Program Above Average, Good Program Average, Minimal Program Below Average, Poor Program No Program	B	3	A	4	C	4	C	4
PIM-4 Inspection / Maintenance Programs	A B C D F	Very Good Program Above Average, Good Program Average, Minimal Program Below Average, Poor Program No Program	D NOTE: Rated Poor	4	B	4	B	4	B	4
PIM-5 Testing Program	A B C D F	Very Good Program Above Average, Good Program Average, Minimal Program Below Average, Poor Program No Program	D NOTE: Rated Poor	4	B	4	B	4	B	4
PIM-6 External Environment (i.e.,vibration)	A B C D F	No Vibration Negligible Vibration Minor Vibration Major Vibration Excessive Vibration	A	3	A	4	A	4	A	4
PIM-7 External Environment (i.e.,corrosion)	A B C D F	 No Corrosion Negligible Corrosion Minor Corrosion Major Corrosion Excessive Corrosion	A	2	B	4	A	4	A	4

Table 8.4 (CONT'D)

SYSTEM 008: Pilot-Plant Flammable-Liquid Day-Tank System

Performance Integrity Measures (PIM)	**SUBSYSTEMS:** **PIM INDICATORS**	**Flexible Hoses** Grade / IMP	**Piping** Grade / IMP	**Pumps** Grade / IMP	**Tank** Grade / IMP
PIM-8 Physical Damage Exposure A B C D F	Not Subject To Negligible Exposure Average Exposure Major Exposure Excessive Exposure	B / 4	A / 4	A / 4	A / 4
PIM-9 Common Cause Failures (i.e., earthquake) A B C D F	Not Subject To Negligible Exposure Average Exposure Major Exposure Excessive Exposure	A / 1	C / 4	B / 4	B / 4
PIM Quality Ratings	* Quality Grade Point Average (GPA)	2.63	3.31	3.33	3.33

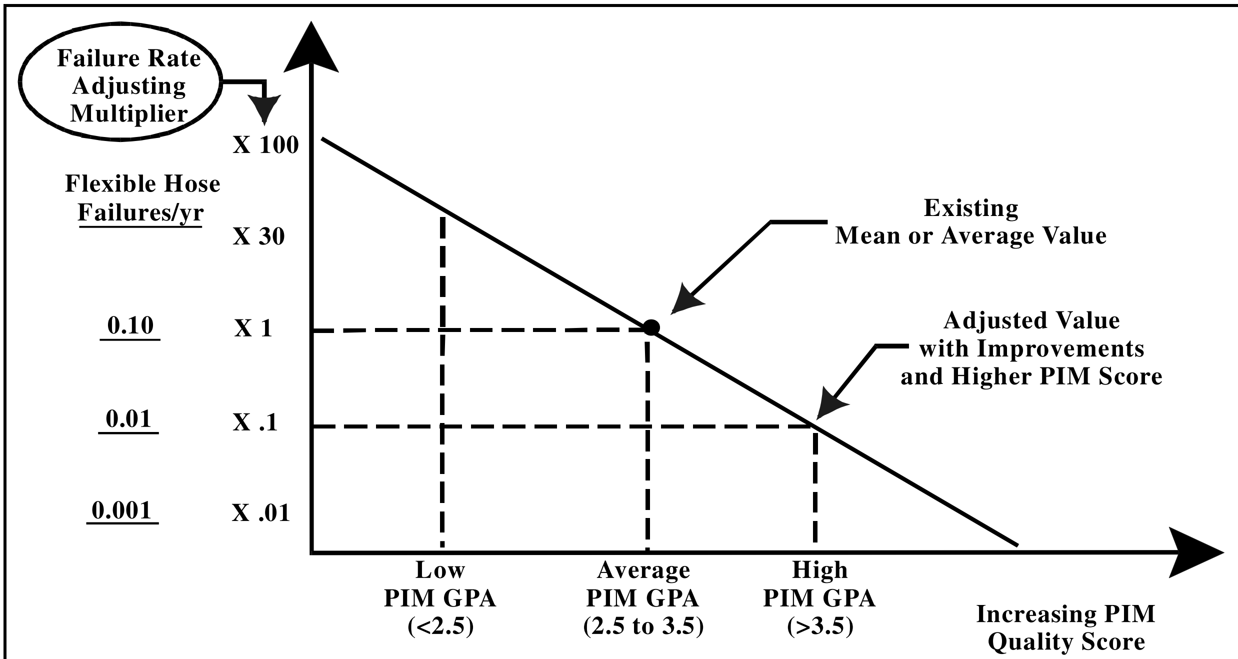
Grading	IMP = Importance
A = 4	4 = Very Important
B = 3	3 =
C = 2	2 =
D = 1	1 =
F = 0	0 = Negligible

* Quality Grade Point Average (GPA) = $\sum_{PIMS}$ Grade X IMP/$\sum$IMP

An example PIM Quality Score versus failure rate profile for the flexible hose is provided in Fig. 8.9. The existing PIM grade is 2.63 (see Table 8.4), which equates to an annualized failure rate of approximately 0.10 failures/year, based on the scale established by the risk assessment team.

By improving the flexible hose maintenance and testing program and completing the management of change program (which would increase the PIM grade to 73.5), the potential annualized failure rate could be decreased to 0.01 failures/year.

Fig. 8.9: Example PIM Quality Score Versus Failure-Rate Adjustment



PIM = Performance Integrity Measure

The adjusted failure rate F_{ADJ} established in this engineering-based scoring model can be equated as:

Low PIM quality Score: $F_{ADJ} = (30 \text{ to } 100) \times F_{Mean}$

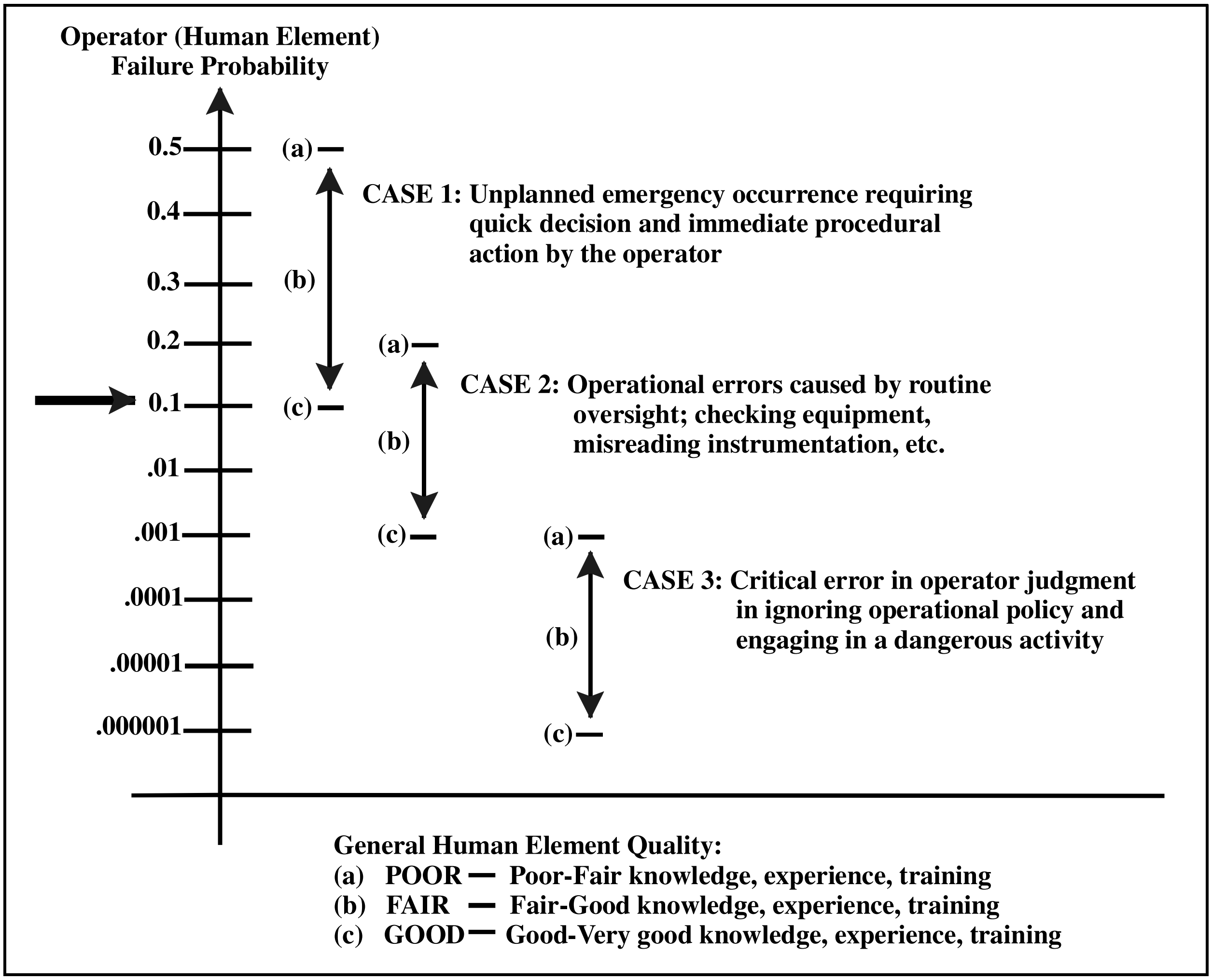
Average PIM Quality Score: $F_{ADJ} = (1) \times F_{Mean}$

High PIM: $F_{ADJ} = (.1 \text{ to } .01) \times F_{Mean}$

8.2.3 Operator Error

In fault tree Fig. 8.8, the likelihood of failure of operator intervention was estimated at 0.10, which was based on an average failure probability potential for a CASE 2 oversight (see Fig. 8.10).

Fig. 8.10: An Example of Human Failure Probability Ranges



Chapter 4 discusses human error. For evaluating more straightforward human factors associated with operator, or maintenance procedures, a procedures analysis worksheet can be used. This technique is primarily deductive and has the simplicity of a general checklist.

Each relevant procedure is broken into steps and questions are posed in three basic categories — Guidance, Feedback, and Correction:

- Guidance – Does the employee know what he or she is supposed to do?
  – Are the operating instructions and training sufficient?
- Feedback – Does the employee know what he or she is doing?
  – Are the displays and gauges adequate to determine the status of the process?
- Correction – Does the employee have the means to take the appropriate action to correct the process?
  – Are the limits of authority clear?

- Are the procedures clear concerning corrective actions and for requesting assistance when actions exceed the technician's authority?
- Does the employee have the tools and ability to operate the controls needed to correct the process?
- Is the training sufficient concerning corrective actions?

Table 8.5 provides an example of a worksheet layout for identifying and analyzing potential human error.

Table 8.5: Example Human Element Procedures Analysis Worksheet

DESCRIPTION OF OPERATION:				PREPARED BY: ____________ DATE: ____________	
HAZARD OR POTENTIAL ERROR	GUIDANCE, FEEDBACK & CORRECTION REQUIRED	RECOMMENDED IMPROVEMENTS	EXISTING FAILURE PROBABILITY	MODIFIED FAILURE PROBABILITY	REFERENCE / REMARKS
			←→ NOTE: Need to Document Justification		

The following information and Table 8.6 are extracted from *A Manager's Guide to Reducing Human Error, Improving Human Performance in the Chemical Industry* by D. K. Lorenzo[1]. Table 8.6 lists five of the major limitations of human reliability analysis (HRA). Some of these may be relatively unimportant for a specific study. However, you must be aware of these limitations when using the results for decision making purposes, and you must understand that *the assumptions made during an HRA are as important as any results*. Therefore, the assumptions should be carefully documented. Despite these limitations, HRA is an extremely valuable tool for identifying and evaluating ways to reduce human errors.

Table 8.6: Major Limitations of HRA[1]

ISSUE	DESCRIPTION
Completeness	There can never be a guarantee that all human errors, extraneous acts, and recovery factors have been considered, nor that everything affecting human behavior has been considered
Validity/Specificity	Probabilistic failure models cannot be completely verified. Human behaviors are observed in experiments and used in model correlations, but models are, at best, approximations of specific circumstances. Some HRA models are based on debatable assumptions about human behavior. The HRA may not provide a good representation of specific plant tasks and PSFs
Accuracy/Uncertainty	The lack of specific data on human error probabilities, PSFs, and accident diagnosis models severely limits accuracy and can produce large uncertainties, especially for prediction of very low-probability human behavior
Reproducibility/Bias	Various aspects of HRA are highly subjective — the results are very sensitive to the analyst's assumptions. The same problem, using identical data and models, may generate widely varying answers when analyzed by different experts, or by the same expert at different times
Traceability/Scrutability	Attempting to understand all the detailed documentation of analyses that led to the HRA results can be an overwhelming, tedious task

Human factors engineering and human reliability analyses can identify and quantify error-likely situations that should be corrected. As indicated in Table 8.7, incorporating well-established human factors engineering principles can help reduce the frequency of errors[1].

Table 8.7: Estimated Decreases in Human Error Probabilities (HEPs) Resulting From Improvements In The Work Situation[1]

IMPROVEMENT	RESULTING DECREASE IN HEPS (FACTORS*)
Good human factors engineering practices in design of controls, displays, and equipment	2 to 10
Use of well-designed written procedures and checklists to replace typical narrative-style procedures	3 to 10
Redesign of displays or controls that violate strong populational stereotypes	over 10
Redesign of valve labeling to clearly indicate each valve's function and its normal operating status	about 5
Frequent practice of the appropriate responses to potential emergencies or other abnormal situations	2 to 10
*These estimated factors are neither directly multiplicative nor additive.	

In our example involving tank overfilling and operator intervention, plant management opts for installing a reliable high level alarm and automatic pump shutdown to reduce the potential for tank overfill. The plant's criterion would be to design this type of system for a minimum 95% reliability, meaning that 95 out of 100 times, high-level conditions would be detected, alarmed, and shutdown. Operator backup would be constantly available and improved procedures and training would be provided.

This type of system would be termed a pre-fire mitigation emergency control system (ECS) and the mechanics for quantifying an ECS are described in Chap. 6, Performance Success Probability of Fire Protection Systems.

8.2.4 Ignition Likelihood

The same approach described in Chap. 4 for quantifying existing ignition likelihood would be used to evaluate ignition likelihood reduction. As stated in Chap. 4, the approach is usually a semi-quantitative one, utilizing engineering judgement to select ignition source strength probabilities from a range such as that presented in Table 8.8.

Table 8.8: Ignition-Source-Strength Probability

IGNITION-SOURCE-STRENGTH RANKING	IGNITION PROBABILITY RANGES	PROBABILITY MIDPOINTS
(S) Strong	.25 – 1.0	.5
(M) Medium	.05 – .24	.15
(W) Weak	.01 – .049	.03

Figure 8.11 presents the ignition fault tree segment from our example (see Fig. 8.8, Event 3.0, Ignition Occurs). Table 8.9 presents an example ignition probability data table. Column G in this table presents the ignition likelihood estimate, which is equated as:

[C] Number of Units / Components	×	[D] Ignition Source Presence Probability	×	[E] Ignition Source Strength Probability	×	[F] Probability Source Is Not Eliminated	=	[G] Ignition Likelihood Estimate

Fig. 8.11: Ignition Probability Estimate

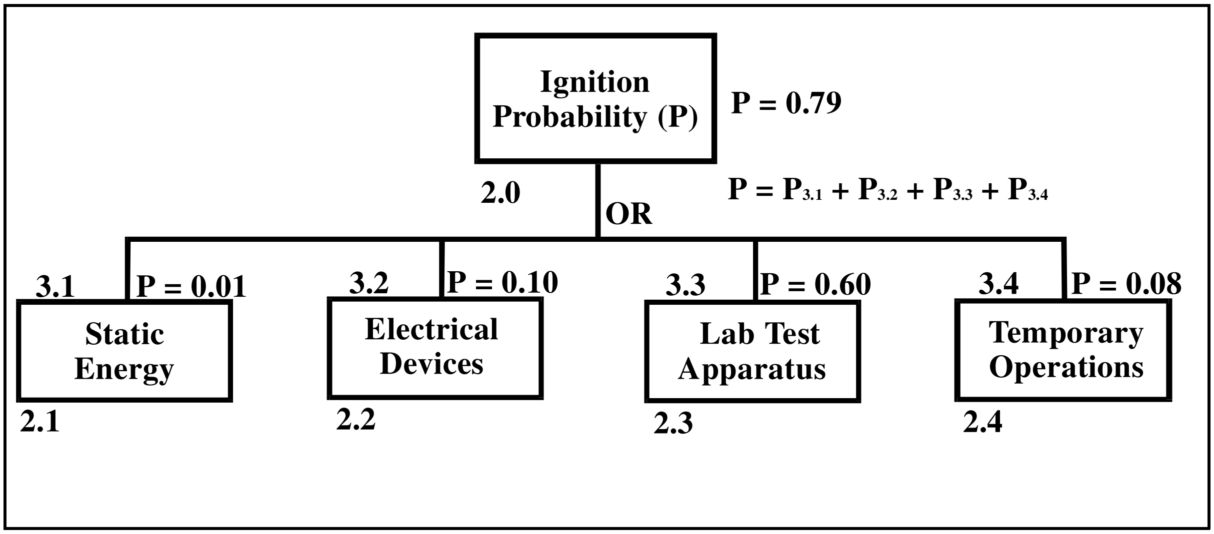


Table 8.9: Ignition Probability Data Table

A ID	B Ignition Source / Description	C Number of Units / Components	D Ignition Source Presence Probability	E Ignition Source Strength Probability	F Probability Source is Not Eliminated	G (C x D x E x F) Ignition Probability Estimate (Ranking)	Reference Source (S)
3.1	Static energy	1 Considered single system	1.0 Continuous potential	0.01 Weak system grounded	1	0.01 (4)	Plant survey Review of grounding system Engineering judgement
3.2	Electrical devices	1 Ordinary electrical devices along west wall	1.0 Continuous potential	0.10 Medium	1	0.10 (2)	Plant survey Engineering judgement
3.3	Lab test apparatus	1 1 lab testing apparatus; has external heating coils.	0.80 Operated approx. 1000 hours per year	0.75 Strong unshielded heating Coils	1	0.60 (1)	Review of design, lab testing equipment. Evaluation of heating coils temperatures.
3.4	Temporary operations	1 Pilot-plant lab operation. Equipment modifications and maintenance work conducted in room	0.08 Approx. 200 hours per year, work is done requiring cutting / welding operations	1.0 Strong hot work	1	0.08 (3)	Review of records and interviews with operations and maintenance

The existing ignition probability related to the lab apparatus is 0.60. Plant management indicates it can replace the lab apparatus with intrinsically safe equipment and operate the equipment less frequently at lower temperatures. Based on engineering review and evaluation of these modifications, the ignition probability has been reduced by 50%, based on engineering judgement:

Modified Ignition Source Presence		Modified Ignition Source Strength Probability		Modified Ignition Probability
60%	×	.50 (strong)	=	0.30

Based on engineering judgement, replacement of the ordinary electrical with classified electrical was estimated as:

Ignition Source Presence		Modified Ignition Source Strength Probability		Modified Ignition Probability
100%	×	0.01 (weak)	=	0.01

8.2.5 Quantification of Likelihood Modifications

Figure 8.12 presents the modified fault tree analysis for our example. The modification options are shown in dotted lines and include:

- Event 1.1 – Leakage Frequency
  Modification: Improve design, inspection and testing of flexible hoses (Event 1.1.2)
- Event 1.2 – Tank Overfilling
  Modification: Add a high-level alarm and automatic pump shutdown as operator backup (Event 1.2.2)
- Event 3.0 – Ignition
  Modification: Install classified electrical (Event 3.2) and replace Lab Apparatus with intrinsically safe unit (Event 3.3)

Based on this example evaluation, there is a reduction of the initiating-fire event likelihood (for our specifically defined fire scenario) from 0.17 fires/year to 0.01 fires/year as presented in Table 8.10.

Table 8.10: Estimated Initiating-Fire Event Likelihood for Example

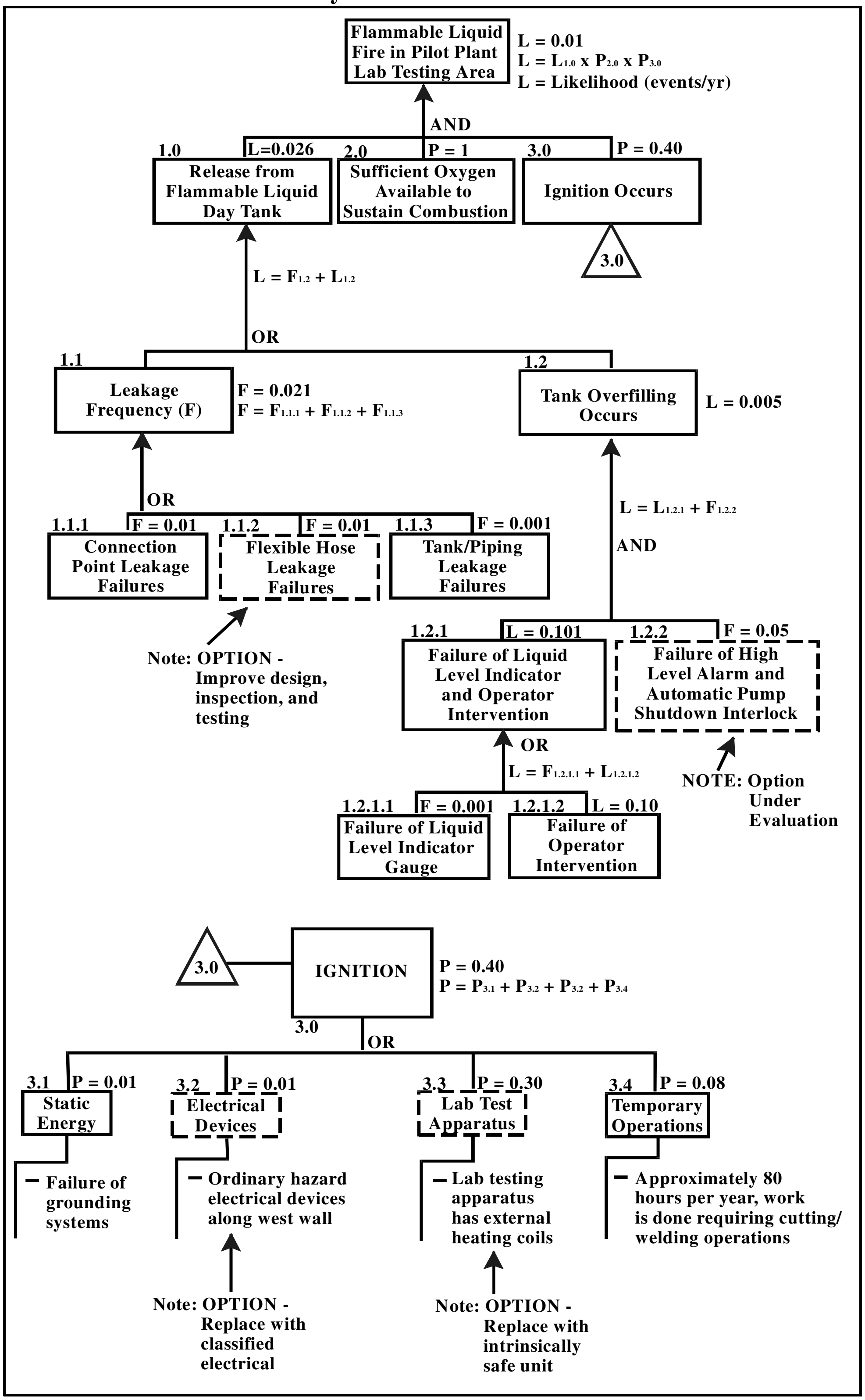
MODIFICATIONS	ESTIMATED INITIATING FIRE EVENT LIKELIHOOD	REMARKS
None	0.17 fires/pilot lab-year or approximately 1 fire every 5–6 pilot lab-years	Refer to Fig. 8.8
All	0.01 fires/pilot lab-year or approximately 1 fire every 100 pilot lab-years	Refer to Fig. 8.12

Table 8.11 illustrates the change in likelihood category based on the modifications discussed in this example.

Table 8.11: Example of Some Initiating Fire Event Likelihood Categories

	LIKELIHOOD CATEGORY	DESCRIPTION	AVERAGE TIME BETWEEN OCCURRENCES (YEARS)	RANGE FREQUENCY (PER YEAR)
	1	Not expected to occur	>300	<003
	2	Not likely to occur during the lifetime of the plant	100–300	.003–.01
b) →	3	Likely to occur no more than once during plant lifetime	30–100	.01–.03
	4	Likely to occur once or twice during plant lifetime	10–30	.03–1
a) →	5	Likely to occur several times during plant lifetime	3–10	.1–3
	6	Likely to occur between once a year and once every three years	1–3	.3–1.0
	7	Likely to occur more than once a year	<1	>1.0
	a = Do no modifications 0.17 fires/pilot lab-year b = Do modifications 0.01 fires/pilot lab-year			

Fig. 8.12: Modified Fault Tree Analysis



The benefits of doing this type of analysis include:

- Within the first-order fault tree framework, major contributors to initiating-fire event likelihood are identified.
- Likelihood reduction alternatives (i.e., failure reduction, oxygen reduction, ignition source controls, etc.) can be quantified.

As stated before, the primary focus should be the identification of the major factors (i.e., weak links) that contribute to the initiating event. Even if historical data are being used, a qualitative fault tree should be structured to ensure recognition and understanding of contributing factors. If event-likelihood reduction is needed, then measures to reduce the likelihood one to two category levels (i.e., Table 8.11) should be developed and quantified in a credible manner. Again, it is important to document data sources and all assumptions made in the analysis.

Following the identification and quantification of alternative measures for reducing the likelihood of initiating fire or explosion events, the costs associated with each alternative or strategy (i.e., a set of alternatives) must be assessed. Cost/benefit analysis of risk reduction alternatives is addressed in Sect. 8.5.

8.3 FIRE PROTECTION SYSTEM PERFORMANCE IMPROVEMENT

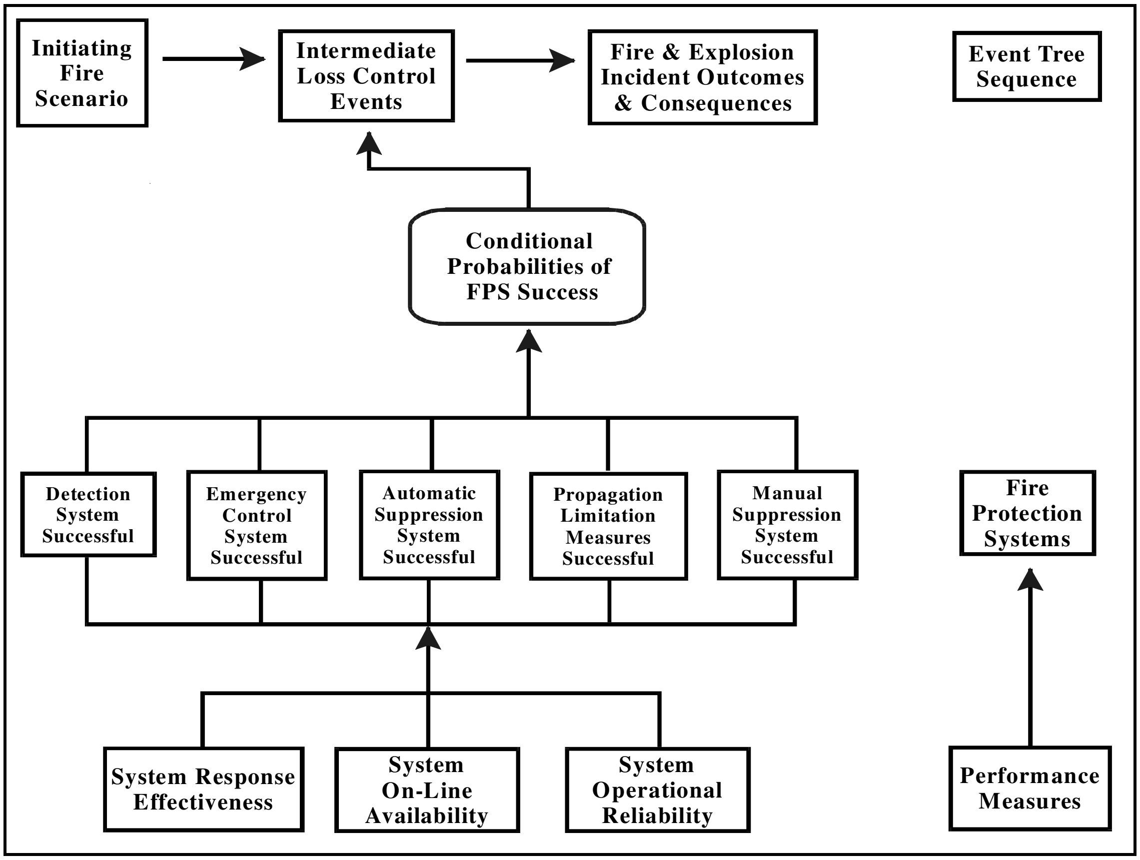
Chapter 6 describes in detail the methods for quantifying the probability of success for FPSs. The beginning of this section provides a brief review. As presented in Fig. 8.13, FPSs of primary interest in fire risk-based evaluations include:

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

Two items to note in Fig. 8.13 are:

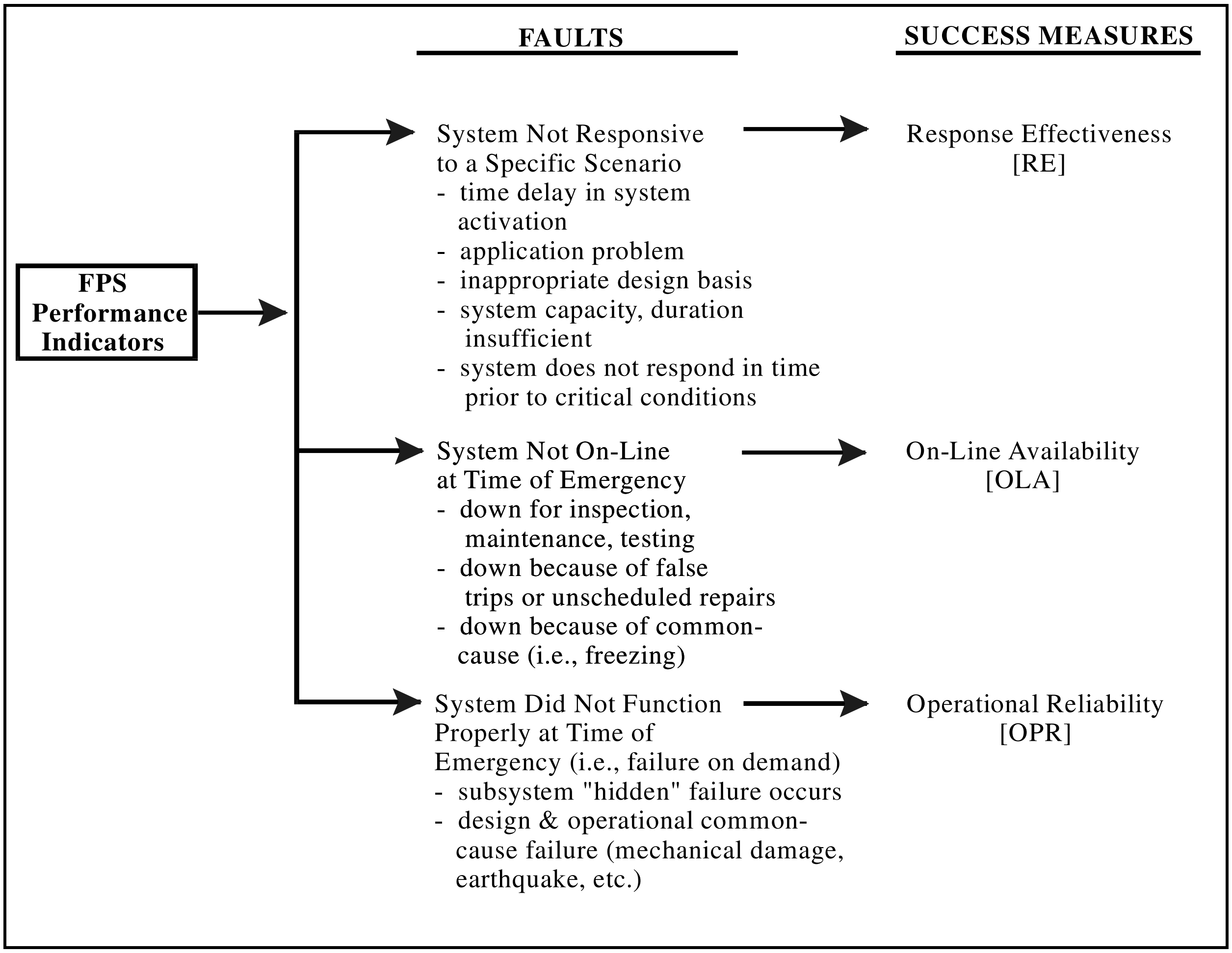
1. FPS performance success is quantified in terms of "conditional probabilities."
2. The three primary FPS performance measures and objectives include:
   - Response effectiveness – maximize system response time
   - On-line availabilities – minimize system downtime
   - Operational reliability – minimize failure-on-demand probability

Fig. 8.13 General Illustration FPS Performance Measures



As stated in Chap. 6, for a defined FPS under a scenario-specific demand, performance success can be evaluated in terms of performance measures and indicators, which are developed from past system failure experience. Figure 8.14 provides an example of some primary success measures.

Fig. 8.14: Example of Primary FPS Success Measures



FPS performance success is the product of these three probabilistic success measures:

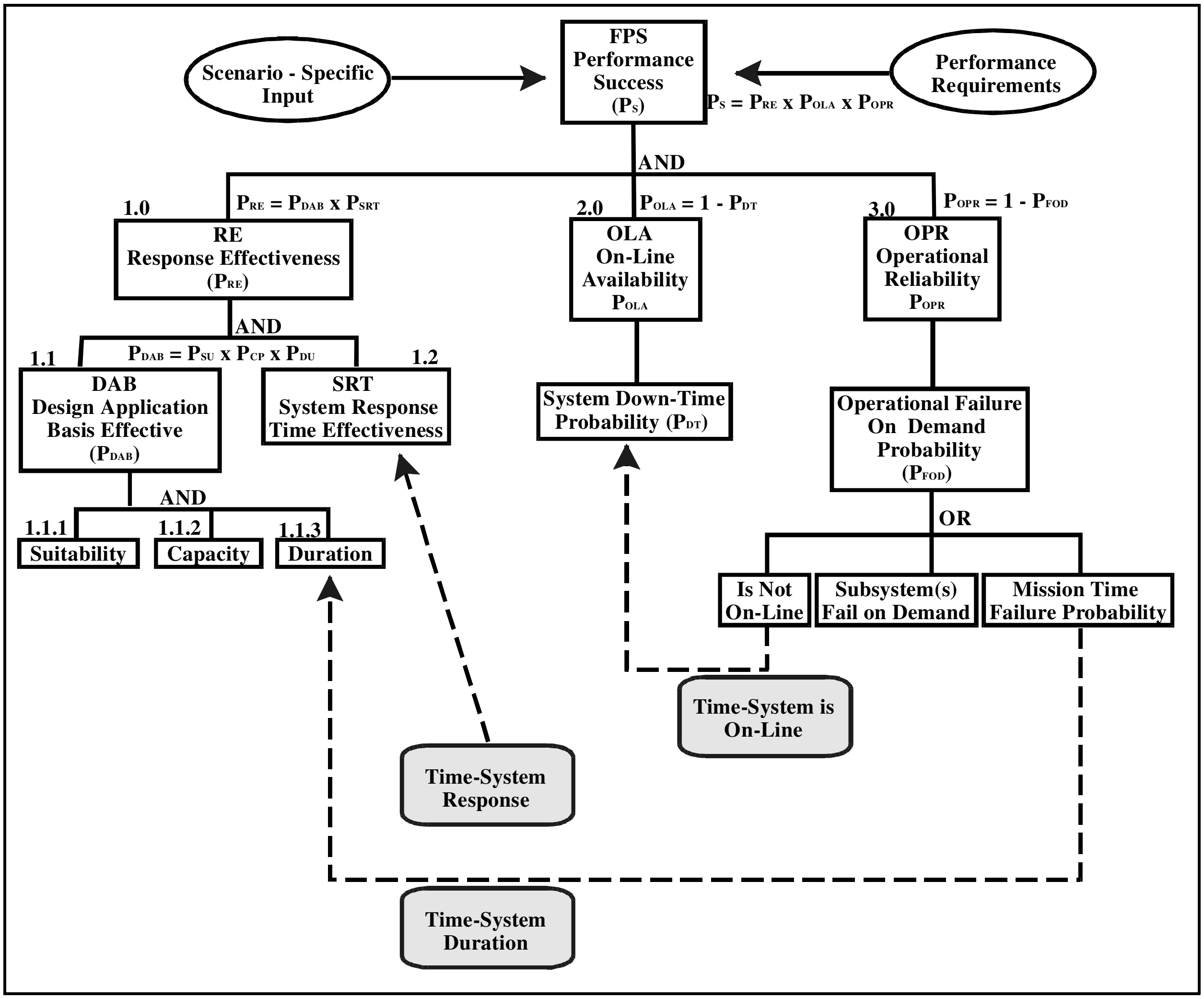
Primary Performance Measure	**RE Response Effectiveness**	**OLA On-Line Availability**	**OPR Operational Reliability**

FPS Performance Success Probability (P_S) $P_S = P_{RE} \times P_{OLA} \times P_{OPR}$

P = probability

Figure 8.15 presents the general FPS success tree logic described in Chap. 6. Figure 8.15 highlights the time-related performance factors which, in many cases, are critical factors and which are not well addressed in current fire codes and standards.

Fig. 8.15: FPS Performance Success Tree Framework—Highlighting Time-Related Performance Factors



At this stage in the risk-informed, performance-based evaluation, the weak links of the analyzed FPSs (existing or proposed) have been identified. With this information, modifications to improve FPS performance can be evaluated.

Improving FPS Performance

It is a good practice to develop an informational data sheet that assists in organizing the performance measures evaluation. Table 8.12 presents an example format. The table is set up to address:

- FPS description/life cycle
- Design-basis fire-scenario description
- Performance requirement
- Response effectiveness (RE)
- On-line availability (OLA)
- Operational reliability (OPR)
- Quantitative tools to support evaluation
- Cost consideration

All of these factors, with the exception of cost, are described in detail in Chap. 6. Cost considerations are addressed in Sect. 8.4 of this chapter.

Table 8.12: Example FPS Performance Information Form

Fire Protection System (FPS) Performance Evaluation

- FPS Description
- Life Cycle
  - ☐ Existing design
  - ☐ Modified design
  - ☐ Proposed new design
- Design-basis fire scenario (describe):
- Evaluation by:
- Date:

Performance Requirement	Response Effectiveness (RE)	On-Line Availability (OLA)	Operational Reliability (OPR)
Minimum requirement 0.95 * FPS performance success probability	**Design Application Bases (DAB)** ☐ Suitability ☐ Capacity ☐ Duration (Mission Time) **System Response Time (SRT)** ☐ Automatic Response Time Criteria ☐ Time Delays in System ☐ Manual Intervention Issues	**Downtime Factors** ☐ Inspection, testing, maintenance (ITM) ☐ False trip, unscheduled repairs (spares) ☐ Common cause failures (freezing, earthquake, etc.)	☐ Subsystem breakdown potentials • Inputs • Control • Outputs (interfaces) ☐ Common cause failures internal design related and external ☐ Performance integrity measures (PIMs)
* Note: Added for example purposes	**Quantitative Evaluation Tools** ☐ Hydraulic models ☐ Heat transfer models ☐ Deterministic response time models	**Quantitative Evaluation Tools** ☐ Plant records – downtime	**Quantitative Evaluation Tools** ☐ Probability of failure-on-demand (P_{FOD}) data

Cost considerations:

Other considerations:

To improve FPS performance, the quantitative success probability of one or all of the following measures must be modified:

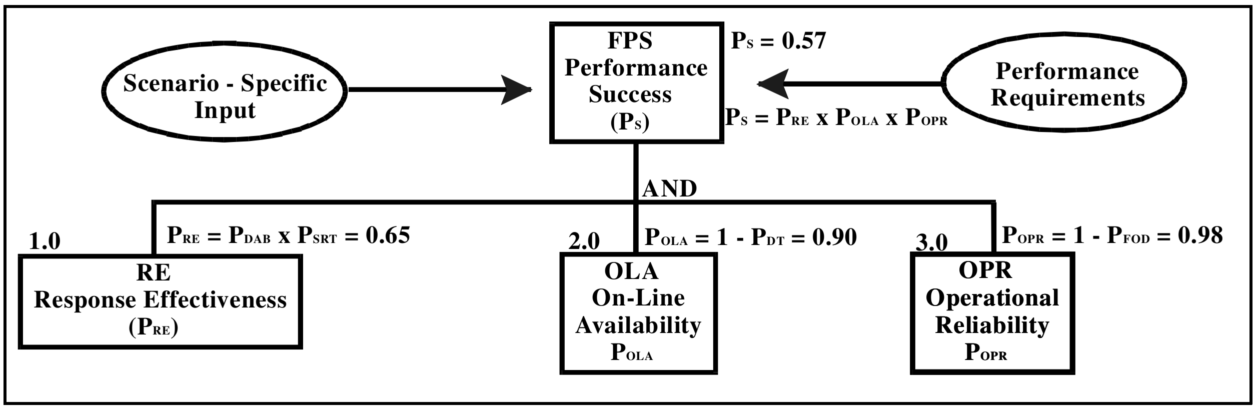
- P_{RE} – Response Effectiveness
- P_{OLA} – On-Line Availability
- P_{OPR} – Operational Reliability

For example, assume an evaluation resulted in an FPS performance success probability, P_S, of 0.57, which would be considered poor for any protection system. This is shown in Fig. 8.16:

$P_S = P_{RE}\ (0.65) \times P_{OLA}\ (0.90) \times P_{OPR}\ (0.98) = 0.57$

The performance improvement analysis in this case would initially focus on modifying the FPS response effectiveness (P_{RE}) and then the on-line availability (P_{OLA}).

Fig. 8.16: Example Primary FPS Performance Success-Tree Factors



There are two items in Fig. 8.16 that are again important to note. First, FPS performance success is based on the "scenario-specific" input. This is usually based on the dominant or upper bound design-basis fires or events being assessed. An FPS that may be successful against a diked combustible pool fire may not be successful against a flammable liquid spray or jet fire, or a smoldering electric signal cable fire, which could cause loss of process control. Second, performance requirements are primarily established in one of two ways: (1) from the event tree risk model, which would indicate a minimal level of performance success to meet established risk tolerance levels (usually applied for "existing" protective systems under risk assessment study) or (2) a minimum requirement for FPS performance success established by a company for all FPSs (i.e., establishing a minimum FPS performance success probability of 0.95 – 0.99 for all installed fire protection systems).

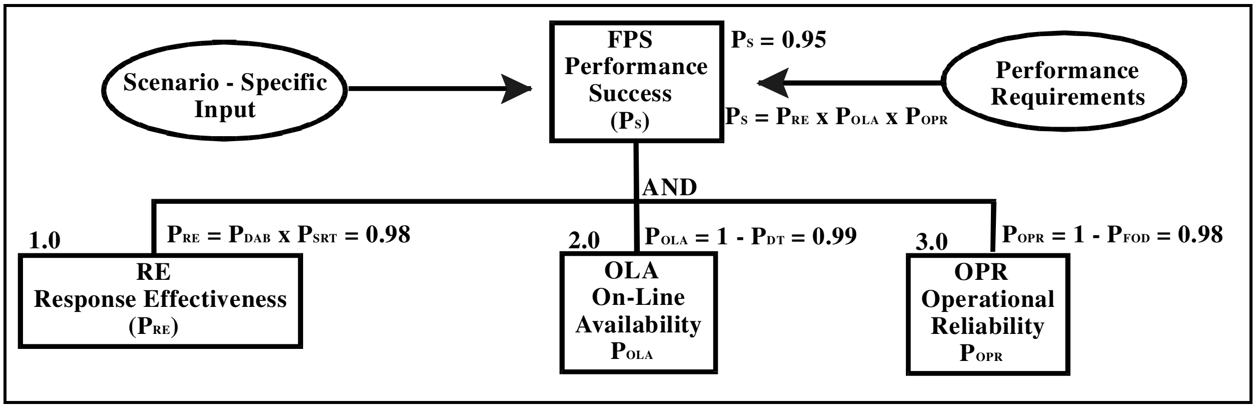
It is interesting that some analysts think a 0.95 probability of FPS performance success is too low. However, if you can modify an FPS or design a new system to provide:

$P_{RE} = 0.98$, $P_{OLA} = 0.99$, and $P_{OPR} = 0.98$,

then the resulting probability of success (P_S) as shown in Fig. 8.17 is:

$P_S = P_{RE}\ (0.98) \times P_{OLA}\ (0.99) \times P_{OPR}\ (0.98) = 0.95.$

Fig. 8.17: Example Modified FPS Performance Success



In many cases, the greatest uncertainty is in the response effectiveness probability (P_{RE}) of the FPS due to the number of potential fire-scenario deviations and variability in such factors as fire growth rates, ventilation conditions, and flame spread.

8.3.1 Improving Performance Success of a Water Spray System

The following presents a simplified example of the steps involved in evaluating the performance upgrade of an existing water spray system. The system:

- Provides exposure protection for critical chemical process equipment that may be exposed to a flammable liquid fire from the adjacent storage tanks,
- Is two years old and was designed to meet applicable design codes, and
- Has to be manually activated at the water spray deluge valve located approximately 30 ft. from the process equipment and storage tanks.

The risk-based assessment team has established the following functional performance requirements for this water spray system:

- Provide cooling of all exposed process equipment at a minimum water application rate of 0.25 GPM per square foot,
- Be operated within 1–3 min,
- Provide water spray cooling for a minimum 30 min to allow process shutdown and fire brigade response, and
- Meet a minimum 0.95 performance success probability.

The general evaluation steps include:

1. Estimate the performance success probability of the existing system.
2. Evaluate opportunities for performance upgrades.
3. Estimate the modified performance of the system based on selected alternatives.

Figure 8.18 illustrates the general performance evaluation framework for this example water spray system. The first step is to quantify the performance success of the existing system based on available information and engineering evaluation.

Design Application Basis

Figure 8.19 presents the design application basis (DAB) logic. The probability data table indicates that probabilities were primarily derived from engineering survey (i.e., on site inspection) and engineering review (i.e., comparison with good engineering practices).

Remember the definition of "risk-informed" involves the integration of quantitative risk assessment tools and traditional engineering methods. For this example, the DAB probability is estimated to be 1.0, assuming the probability selection basis in Fig. 8.19.

Fig. 8.18: Example Water-Spray System Performance Evaluation Framework

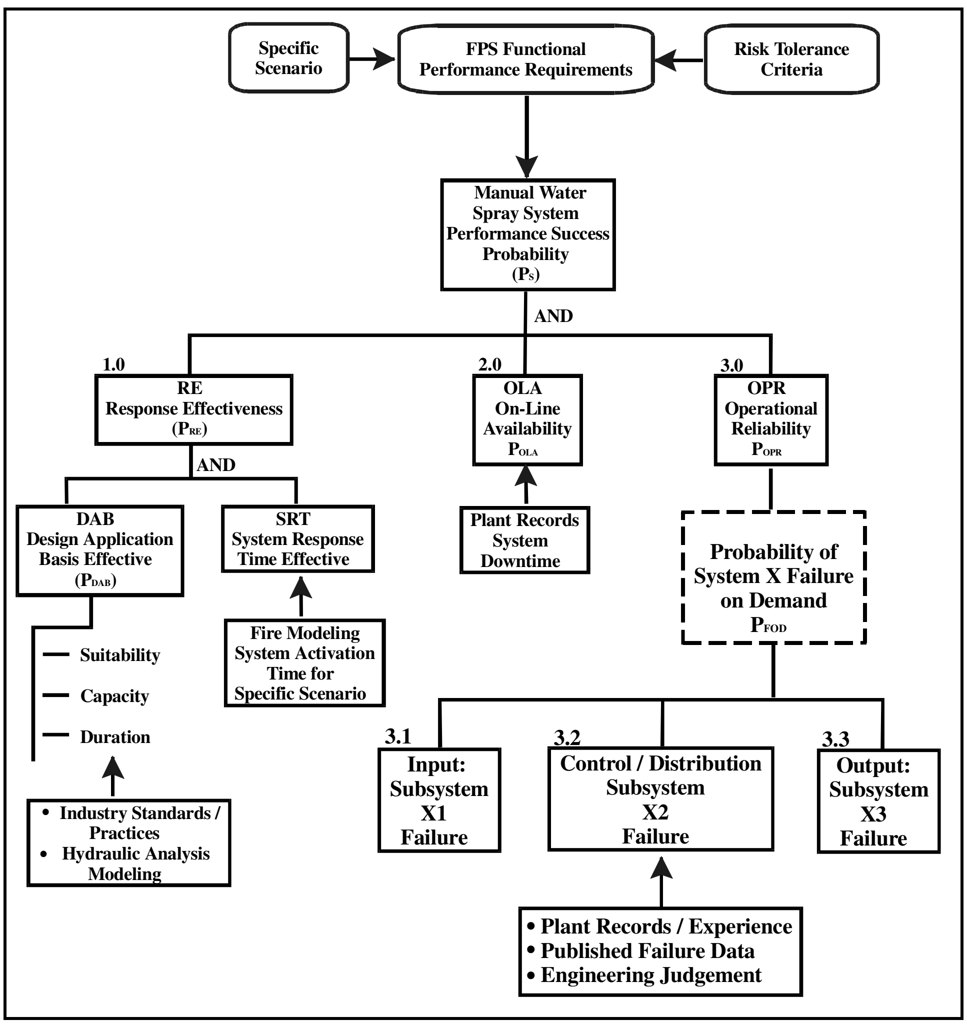
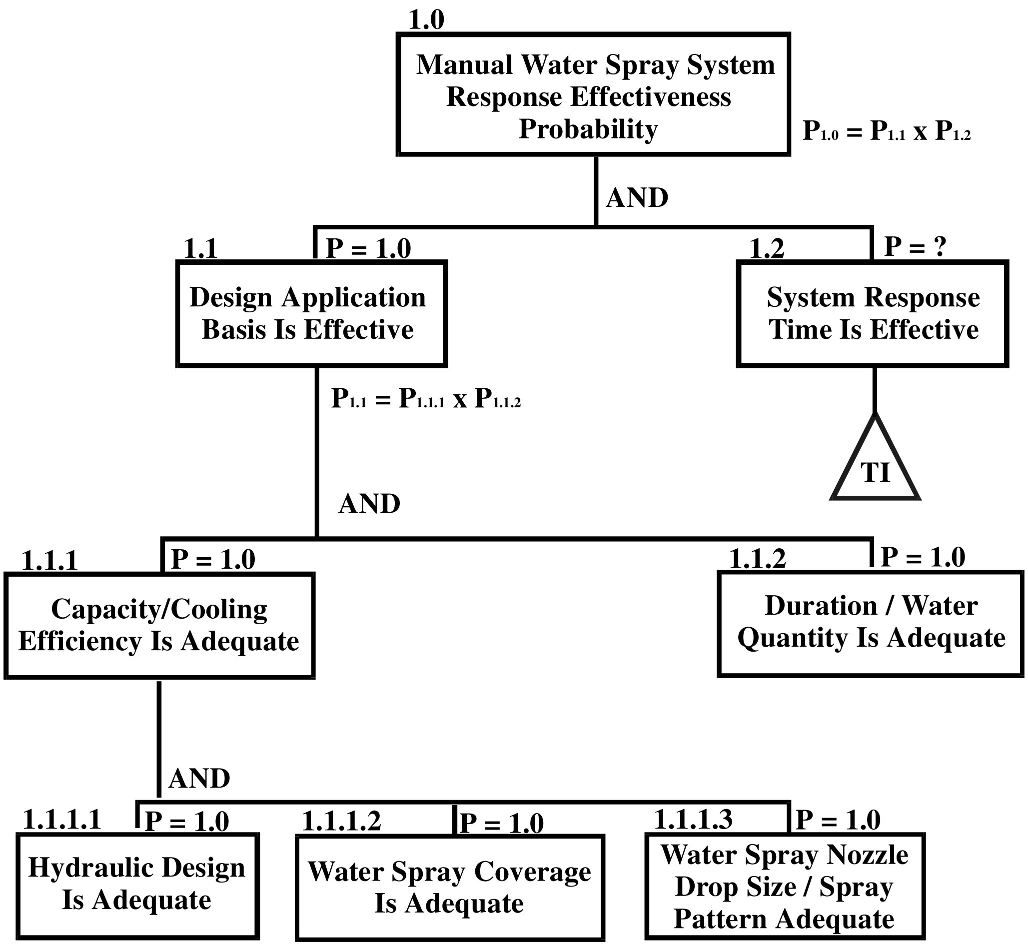


Fig. 8.19: Example Water-Spray System Design Application Effectiveness



Probability Data Table

I.D.	EVENT	PROBABILITY	PROBABILITY SELECTION BASIS
1.1.1.1	Hydraulic design is adequate	1.0	Computerized hydraulic modeling was performed using software XXX
1.1.1.2	Water spray coverage is adequate	1.0	Based on engineering site inspection
1.1.1.3	Water spray nozzle drop size/spray pattern adequate	1.0	Based on observation of a system test
1.1.2	Duration/water quantity is adequate	1.0	Based on engineering review and evaluation

Primary probability sources for use in evaluating the DAB segment of the system response effectiveness include:

1. Experience
2. Deterministic Models
3. Engineering Judgement

1. *Experience*

- Standards, industry practices
- Plant, industry-specific experience
- Loss incident data
- Research and testing

2. *Deterministic Modeling*

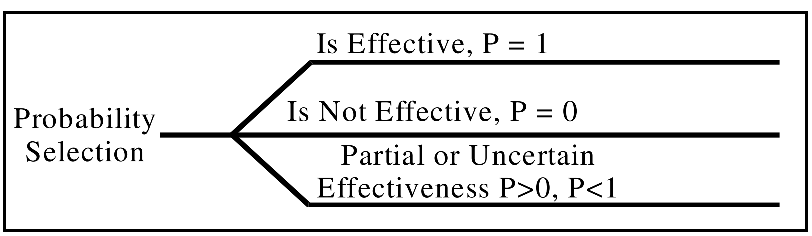
Models to support DAB probability evaluations can include:

- Hydraulic models
- Heat transfer models

3. *Engineering Judgement*

In the majority of cases based on items 1 and 2 above we will be able to select the following probability (P) estimation:

P = 1 DAB is effective.
P = 0 DAB is not effective.



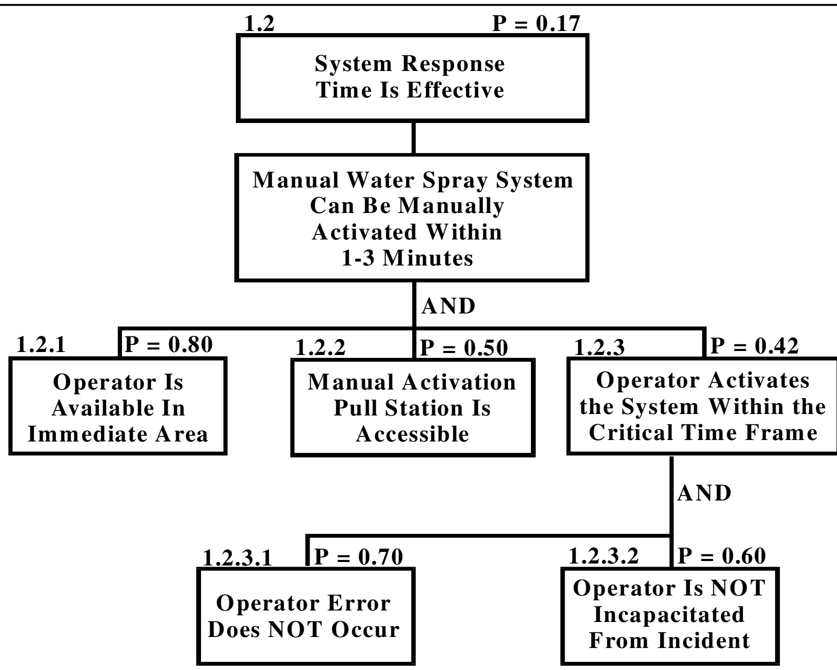
In some cases, however, there may be uncertainty due to insufficient knowledge or experience. Engineering judgement usually involves reviewing information obtained from probability sources 1 and 2 and applying expert opinion and team consensus.

System Response Time

Figure 8.20 presents the SRT logic. The water spray system, as presently designed, is manual. The process area is attended 80% of the time. Based on performing radiant-heat pool-fire modeling for the specific fire scenario, it was determined that approximately 35% of the time, wind effects could create a situation where the pool-fire heat exceeded 5KW/m^2 incident radiant heat flux, which was considered a limit for operator accessibility to the manual activation station. Therefore, based on the fire modeling and conservative engineering judgement, a 0.50 probability was applied to the event manual activation pull station is accessible during a fire emergency.

Concerning operator error or misjudgement in manual operation of this system, a Case 1(b) human failure probability of 0.30 was applied (0.70 probability of success) based on engineering review of operator knowledge, experience, and training (refer to Fig. 8.10).

Fig. 8.20: Response Time Effectiveness for Example Manual Water-Spray System



Probability Data Table

I.D.	EVENT	PROBABILITY	PROBABILITY SELECTION BASIS
1.2.1	Operator is available in immediate area	0.80	Based on plant information, there is an operator available in the area 80% of the time
1.2.2	Manual activation pull station is accessible	0.50	Based on radiant-heat pool-fire modeling (see attachment 002) and engineering judgement
1.2.3.1	Operator activates the system within the critical time frame. Operator error does not occur.	0.70	Based on engineering review of operator knowledge, experience, and training, a CASE 1(b) failure probability (0.70 success probability) was applied (refer to Fig. 8.10)
1.2.3.2	Operator is not incapacitated from fire incident.	0.60	Based on engineering judgement and fire modeling results

On-Line Availability

Figure 8.21 presents the OLA logic. The “system” includes the water spray components, the water supply piping that feeds the water spray system, and the water supply tank and fire pump.

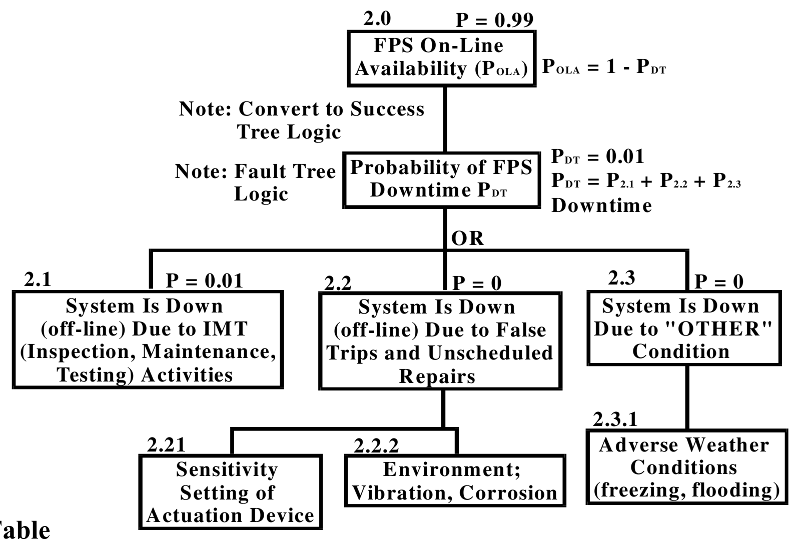
Based on engineering review of Plant Maintenance Department records and system testing and impairment records, the maximum downtime for IMT activities was found to be 60 hours per year:

60 hours downtime ⁄ 8760 hours/year = 0.0068 downtime probability per year.

This was rounded up to an annual downtime probability, P = 0.01.

Based on further engineering review, there were no false trip or adverse weather-related system downtime factors.

Fig. 8.21: OLA Manual Water Spray System Success Tree Logic



Probability Data Table

I.D.	EVENT	PROBABILITY	PROBABILITY SELECTION BASIS
2.1	System is down due to IMT activities	0.01	Based on engineering review of plant maintenance department IMT records
2.2	System is down due to false trips	0	Manual system
2.3	System is down due to other condition such as adverse weather	0	No recorded historical incidents

Operational Reliability

Figure 8.22 presents the Operational Reliability (OPR) logic. The focus in this evaluation is the system "Failure On-Demand" probability.

Figure 8.22 is broken down into two primary failure events:

3.1 Failure of the water spray system to operate on-demand
3.2 Failure of having adequate pressure and water flow at the water spray nozzles

Figure 8.23 is a continuation of Fig. 8.22, presenting a qualitative fault tree structure of contributing factors such as the water supply tank and pump failure and water distribution system failure. OPR is addressed in detail in Chap. 6. The approach taken in this example involves the following:

- Perform qualitative fault tree structuring of contributing failure factors (as in Figs. 8.22 and 8.23). Note: The most important aspect of OPR is to identify, recognize, and understand the primary failure modes and contributing factors.
- Evaluate system Performance Integrity Measures (PIMs) in terms of quality scoring and importance.
- Select probabilities for failure-on-demand (P_{FOD}) and document the data sources.
- Recognize uncertainty issues.

Fig. 8.22: Operational Reliability Evaluation Framework for Example Water Spray System

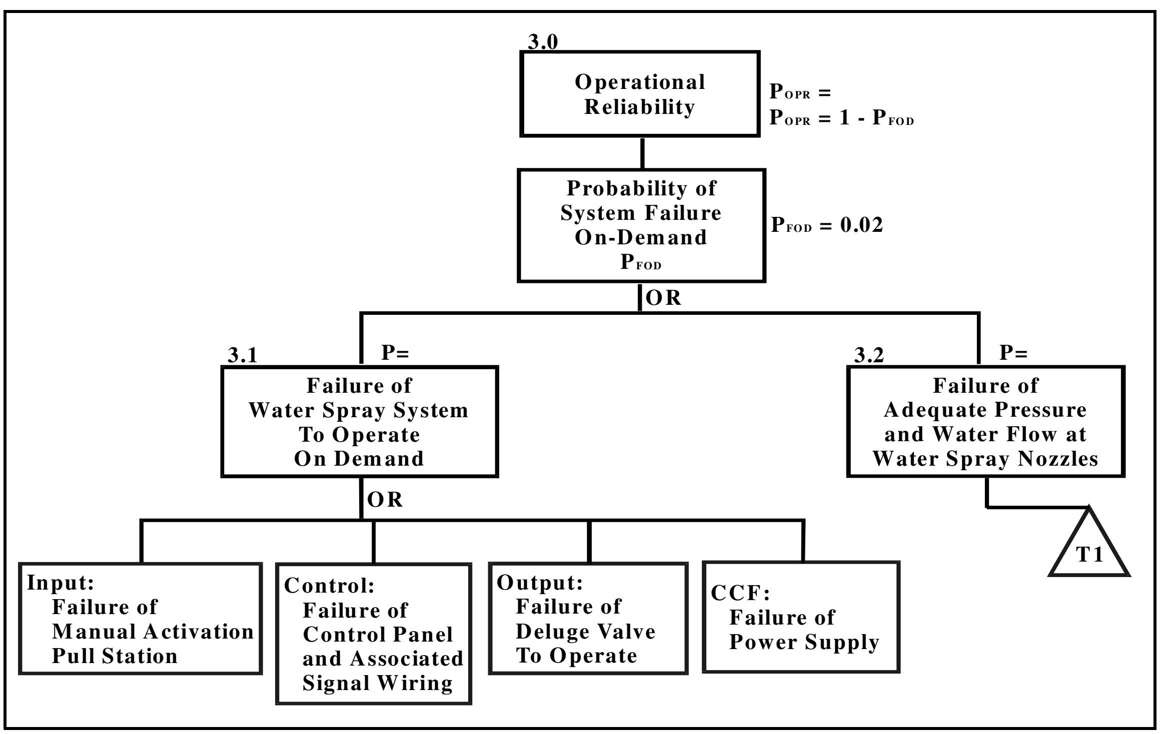
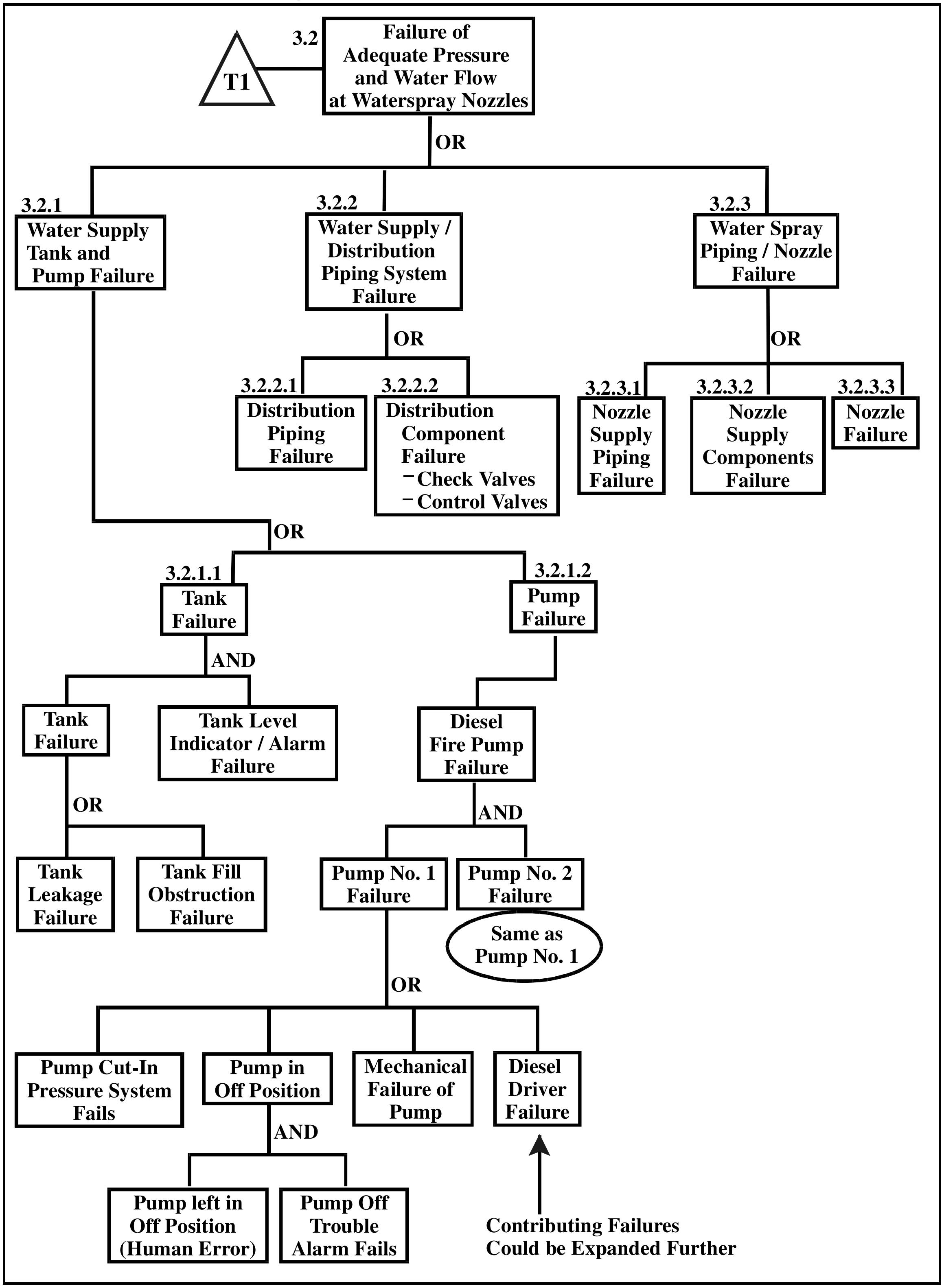


Fig. 8.23: Continuation of Fig. 8.22



Operational Reliability – Performance Integrity Measures

Table 8.13 presents a PIM quality scoring worksheet for the primary fault tree events, which include:

3.1 Water spray actuation systems and power supply
3.2.1 Water supply tanks and pumps
3.2.2 Water supply distribution piping
3.2.3 Water spray system valves, piping, nozzles

Based on plant site surveys and engineering reviews, the following PIM indicators were selected and graded:

PIM-1 General Design Standards
PIM-2 Life-Cycle (Age)
PIM-3 Management of Change Program
PIM-4 Inspection/Maintenance Programs
PIM-5 Proof-Testing Program
PIM-6 External Environment (Vibration)
PIM-7 External Environment (Corrosion)
PIM-8 Subject to Physical Damage
PIM-9 Diagnostics

The first column in example Table 8.13 lists significant PIMs and PIM indicators. Indicators provide primary grading factors, A⟶F.

Grading: A = 4 – Very high-quality program
B = 3 ↓
C = 2
D = 1 – Very low-quality program
F = 0 – No program

The FPS subsystems are graded based on engineering reviews and evaluations. Importance (IMP, a type of weighting) is assigned to each PIM in relation to the subsystem being evaluated. The importance in this example table is based on:

IMP: 4 = Very important
3 ↓
2
1
0 = Negligible

Table 8.13 Example PIM Quality Scoring Sheet

SYSTEM: Water Spray System for Process KLM

Performance Integrity Measures (PIM)		PIM INDICATORS	3.1 Water Spray Actuation Systems & Power Supply Grade	3.1 IMP	3.2.1 Water Supply Tank and Pumps Grade	3.2.1 IMP	3.2.2 Water Supply Distribution System Piping Grade	3.2.2 IMP	3.2.3 Water Spray System Valves, Piping, Nozzles Grade	3.2.3 IMP
PIM-1 General Design Standards	A	Designed per NFPA, Current Edition	A	4	A	4	A	4	A	4
	B	Designed per NFPA, Older Edition								
	C	Minor deviations from NFPA								
	D	Major deviations from NFPA								
	F	Not designed per NFPA								
PIM-2 Life-Cycle (Age)	A	Newer Equipment, Formally Acceptance Tested	B	4	B	4	B	4	B	4
	B	Newer, not Formally Accepted Tested								
	C	At or Slightly Below ½ Useful Life								
	D	Above ½ Useful Life								
	F	At end of Useful Life								
PIM-3 Management of Change Program	A	Very Good Program	A	4	A	4	A	4	A	4
	B	Above Average, Good Program								
	C	Average, Minimal Program								
	D	Below Average, Poor Program								
	F	No Program								
PIM-4 Inspection / Maintenance Programs	A	Very Good Program	A	4	A	4	A	4	A	4
	B	Above Average, Good Program								
	C	Average, Minimal Program								
	D	Below Average, Poor Program								
	F	No Program								
PIM-5 Proof-Testing Program	A	Very Good Program	A	4	A	4	A	4	A	4
	B	Above Average, Good Program								
	C	Average, Minimal Program								
	D	Below Average, Poor Program								
	F	No Program								
PIM-6 External Environment (i.e., vibration)	A	No Vibration	A	3	A	3	A	3	A	3
	B	Negligible Vibration								
	C	Minor Vibration								
	D	Major Vibration								
	F	Excessive Vibration								
PIM-7 External Environment (i.e., corrosion)	A	No Corrosion	A	4	A	4	A	4	A	4
	B	Negligible Corrosion								
	C	Minor Corrosion								
	D	Major Corrosion								
	F	Excessive Corrosion								

IMP = Importance

Table 8.13 (CONT'D)

SYSTEM: Water Spray System for Process KLM

Performance Integrity Measures (PIM)	PIM INDICATORS (SUBSYSTEMS:)	3.1 Water Spray Actuation Systems & Power Supply Grade / IMP	3.2.1 Water Supply Tank and Pumps Grade / IMP	3.2.2 Water Supply Distribution System Piping Grade / IMP	3.2.3 Water Spray System Valves, Piping, Nozzles Grade / IMP
PIM-8 Subject to Physical Damage A, B, C, D, F	A Not Subject to ↓ F Very Subject to	B / 4	A / 4	A / 4	B / 4
PIM-9 Diagnostics (Fault Detection) A, B, C, D, F i.e., Supervisory and Trouble Alarms	A Very Good Diagnostics ↓ D No Diagnostics	A / 4 Power Supply Supervision	A / 4 Tank Level & Pump Trouble Alarms	B / 4 Valve Supervisio n	A / 4 Valve Supervision
PIM Quality Ratings	* Quality Grade Point Average (GPA) →	3.77	3.88	3.66	3.77
	GRADE →	Very High	Very High	Very High	Very High

Grading: A = 4, B = 3, C = 2, D = 1, F = 0

IMP = Importance: 4 = Very Important, 3 =, 2 =, 1 =, 0 = Negligible

* Quality Grade Point Average (GPA) = $\sum_{\text{PIMs}}$ Grade X IMP / $\sum$ IMP

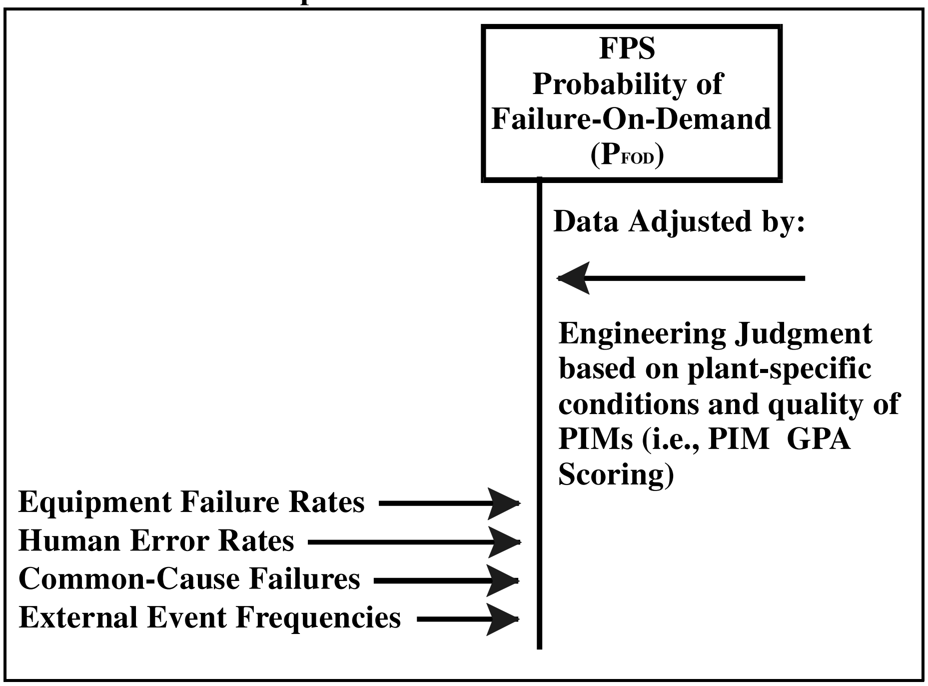
For the purpose of this example, the PIMs for events 3.1, 3.2.1, 3.2.2, and 3.2.3 were all graded Very High (refer to last row in table 8.13). This generally means that you would apply mean to lower value failure-rate data and would expect a high system reliability rating.

Relating PIM Scores to Failure-On-Demand Probability

There are two primary approaches for selecting probability of failure-on-demand (P_{FOD}). The first one is to compile failure rate data, develop failure bandwidths, and estimate mean failure rates, then adjust or modify the mean value based on the PIM score and engineering judgement. (Note: this technique is discussed in Chap. 6). These data are then used in the FTA.

As illustrated in Fig. 8.24, numerous failure data inputs may be needed to assess the overall failure-on-demand potential. In many cases, the failure data will have to be adjusted or modified based on plant specific conditions, the quality grading of the PIMs, and engineering judgement.

Fig. 8.24 Some Failure Data Inputs



Tables 8.14, and 8.15, and Fig. 8.25 provide some examples of failure-on-demand probability data that could be applied in an FTA. Table 8.14 indicates a reliability of 0.99 for an open-head manual water spray system (note: operational reliability = 1 – P_{FOD}; = 1 – 0.0056).[2] Figure 8.25 indicates a mean reliability of 0.98 for an electric fire pump (note: 1 – (18.7/1,000) = 0.98), assuming the mean value P_{FOD}.[3]

Table 8.14: FPS Failure Rates[2]

TYPE OF SYSTEM	PROBABILITY OF FAILURE TO OPERATE ON-DEMAND: NFPA INSPECTION INTERVALS	PROBABILITY OF FAILURE TO OPERATE ON-DEMAND: YEARLY INSPECTION INTERVALS
Manual spray — open head	0.0056	0.0056
Manual spray — closed head	0.0056	0.0056
Automatic sprinkler — wet pipe		
— without limit switches on isolation valve	0.00067	0.028
— with limit switches on isolation valve	0.00015	0.00092

Table 8.15: Comparison of Fire Detector Reliablilities[2]

DETECTOR TYPE	FAIL TO OPERATE FAILURES/1000 DETECTOR-YEARS	FALSE ALARMS FAILURES/1000 DETECTOR-YEARS
Heat (all types)	0.3	9.02
Photoelectric (smoke)	0.5	536.0
Ultraviolet	108.0	200.0
Infrared	108.0	2,135.0
Ionization (smoke)	(1)	186.0

(1) Data not available

Fig. 8.25: Example of Fire Pump Failure Data Table[3]

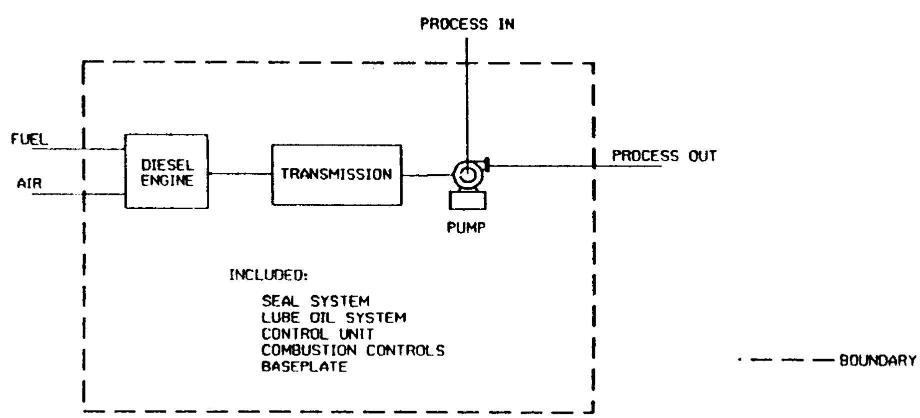
DATA ON SELECTED PROCESS SYSTEMS AND EQUIPMENT

Taxonomy No.	4.2.4.1	**Equipment Description**	PROTECTION SYSTEMS-FIRE- FIRE WATER PUMPS - DIESEL
Operating Mode	STANDBY	**Process Severity**	UNKNOWN

Population	**Samples**	**Aggregated time in service (10^6 hrs)**		**No. of Demands**
		Calendar time	**Operating time**	

Failure mode	**Failures (per 10^6 hrs)**			**Failures (per 10^3 demands)**		
	Lower	**Mean**	**Upper**	**Lower**	**Mean**	**Upper**
CATASTROPHIC						
a. Fails to Start				0.769	18.7	69.8
b. Fails While Running						
DEGRADED						
a. Low Output						
INCIPIENT						
a. Vibration						
b. Leakage						

Equipment Boundary



Data Reference No. (Table 5.1): 8, 8.9, 8.11

American Institute of Chemical Engineers (AIChE). Center for Chemical Process Safety (CCPS), *Guidelines for Process Equipment Reliability Data With Data Tables*, New York, NY, 1989.

With knowledge and experience involving failure rate ranges and contributing factors from previous evaluations, a relationship between PIM quality scoring and P_{FOD} can be established. An example of this is shown in Table 8.16.

Table 8.16: Example Relating PIMs to P_{FOD} Ranges

PIM SCORE / GRADE	RELIABILITY RANGE		PROBABILITY OF FAILURE-ON-DEMAND (P_{FOD}) (≈ 1 – RELIABILITY)	
Very high	Very high	.99 – .999	Very low	.01 – .001
↓	High	.95 < .99	Low	.05 < .01
	Average	.90 < .95	Average	.10 < .05
	Low	.80 < .90	High	.20 < .10
Very low	Very low	< .80	Very high	> .20

As presented in Fig. 8.26, the Operational Reliability for this example water spray system is estimated at 0.98. Table 8.17 provides a probability selection basis for this first-order FTA. The engineering judgements applied the relationships to Table 8.16.

Fig. 8.26: Operational Reliability Evaluation for Example Water Spray System

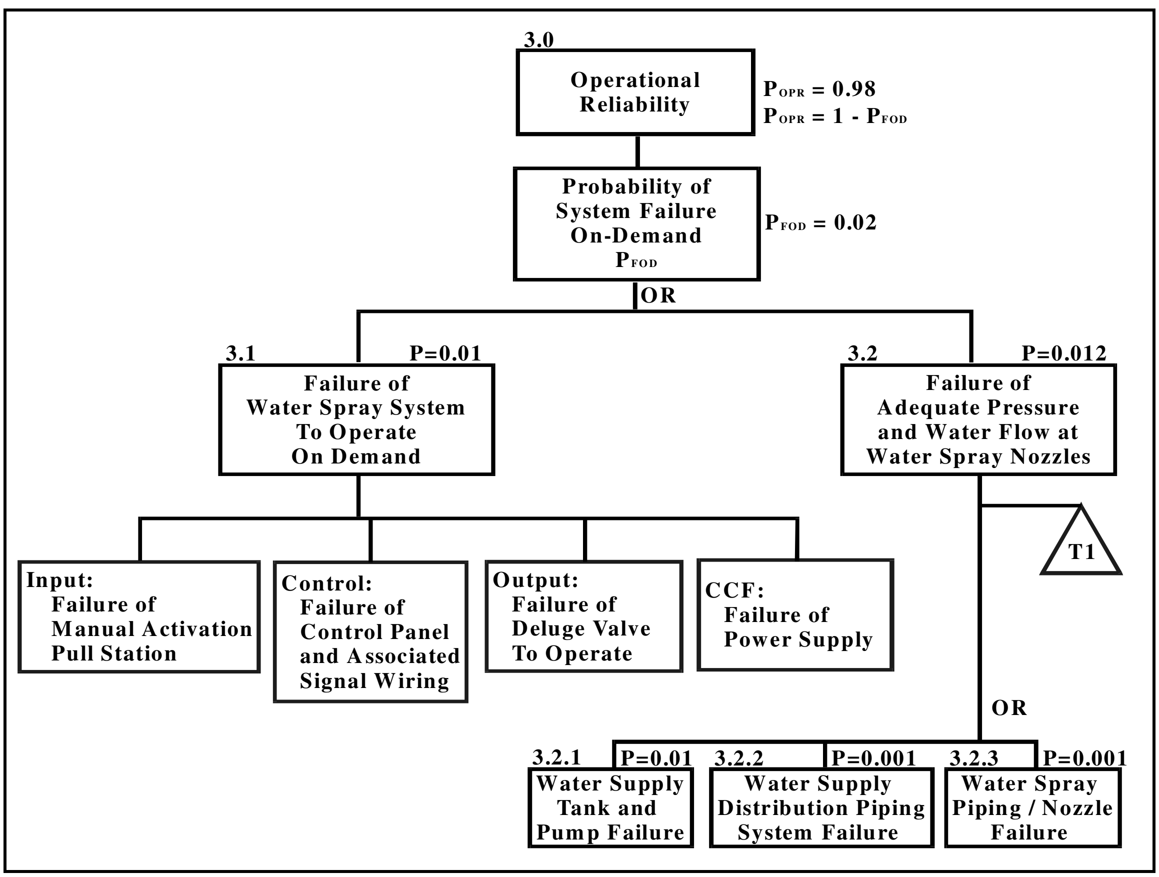


Table 8.17: Example Failure-On-Demand Probability Data Table

I.D.	EVENT	PIM SCORE*	P_{FOD}	PROBABILITY SELECTION BASIS**
3.1	Actuation system for water spray system & power supply	Very high	0.01	Failure rate data and engineering judgement
3.2.1	Water supply tank and pumps	Very high	0.01	Failure rate data, Fig. 8.25 and engineering judgement
3.2.2	Water supply piping distribution system	Very high	0.001	Engineering analysis and judgement
3.2.3	Water spray system valves, piping, nozzles	Very high	0.001	Failure rate data, Table 8.14 and engineering judgement

* Refer to Table 8.13, PIM Quality Scoring Sheet
** In practice, specific failure rate data references would be listed

Existing Water Spray System – Opportunities for Improvement

Based on performance quantification of the example existing water spray system (existing probability of success is 0.27), the biggest opportunity for upgrade is improving the system response time. As presented in Fig. 8.27, if the required performance-success probability is 0.95, then the system response time (event 1.2, P = 0.28) will have to be improved.

Fig. 8.27: Performance Evaluation Framework for Example Existing Manual Water Spray Systems

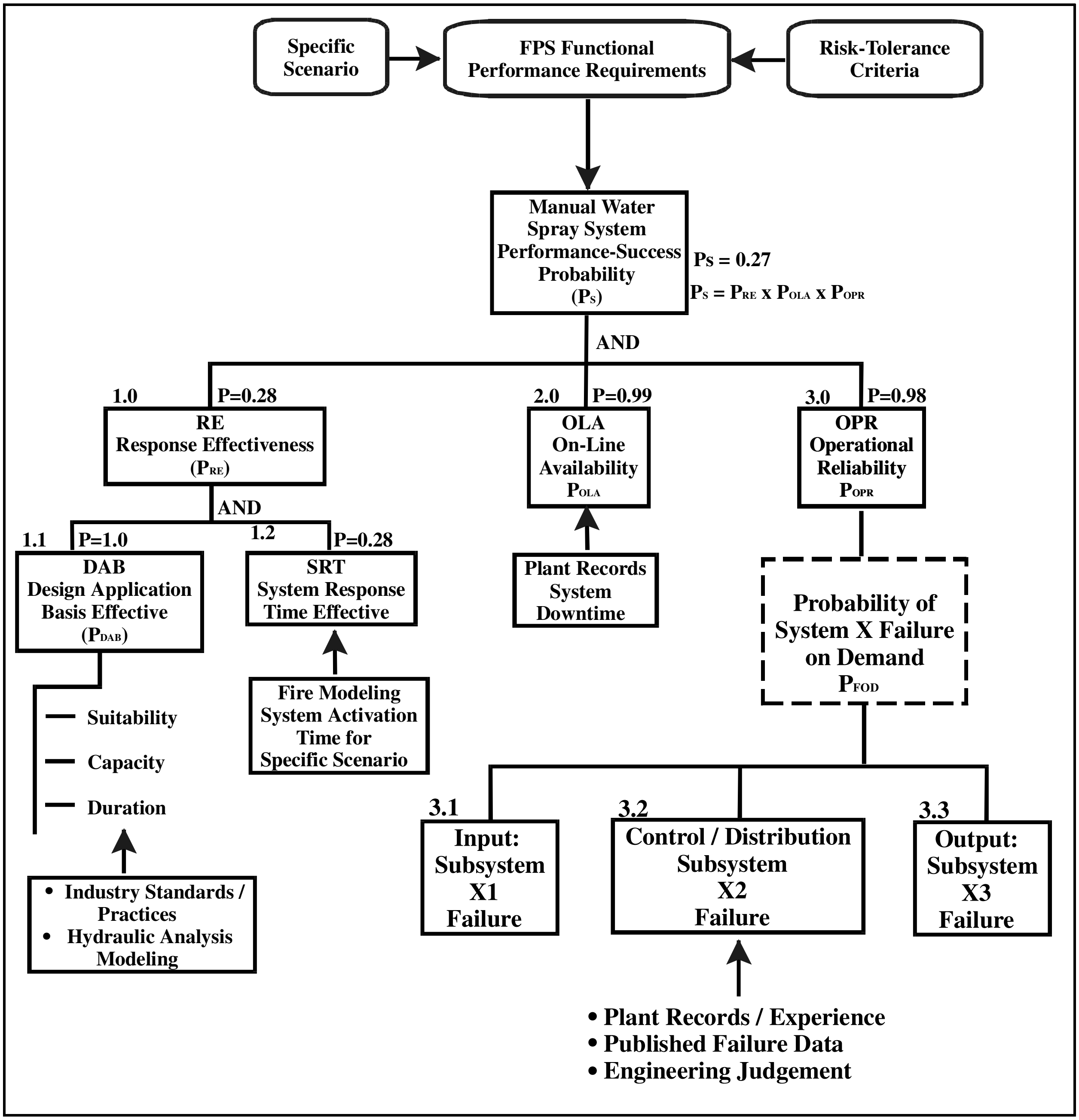
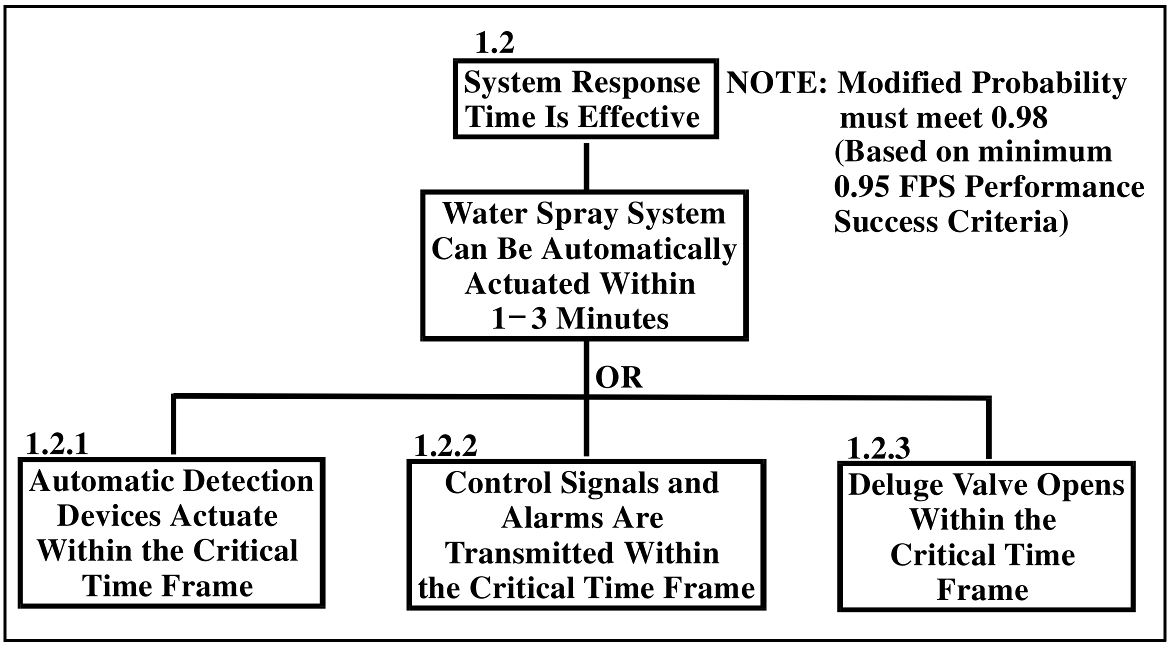


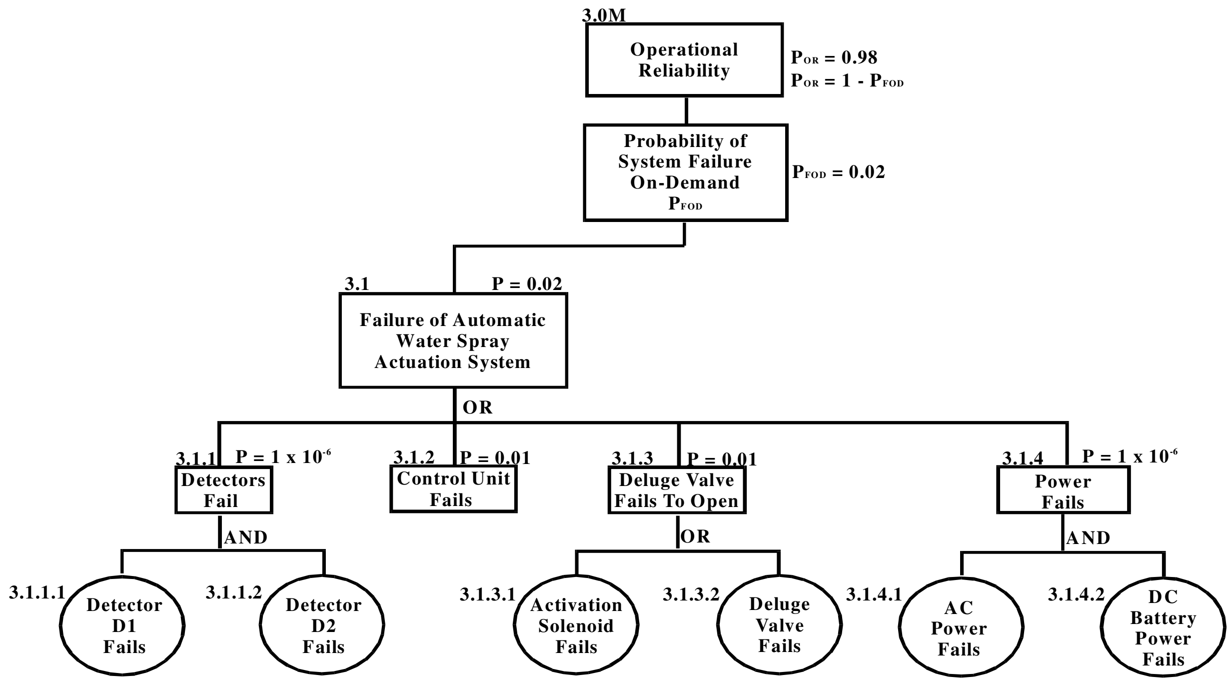
Figure 8.28 presents a modification to the example water-spray system, which consists of adding automatic detection and activation to improve the system response time. As noted in this figure, the modification must improve the system response time probability to 0.98.

Fig. 8.28: Response Time Effectiveness Logic for Example Water Spray System-Adding Automatic Detection and Activation



In addition to the modified response time evaluation of the proposed automatic detection and actuation system, the operational reliability of the proposed design would also have to be examined. Figure 8.29 presents an example of the FTA logic for this sort of evaluation. The probabilities have been added for example purposes.

Fig. 8.29: Operational Reliability for Modified Water-Spray System

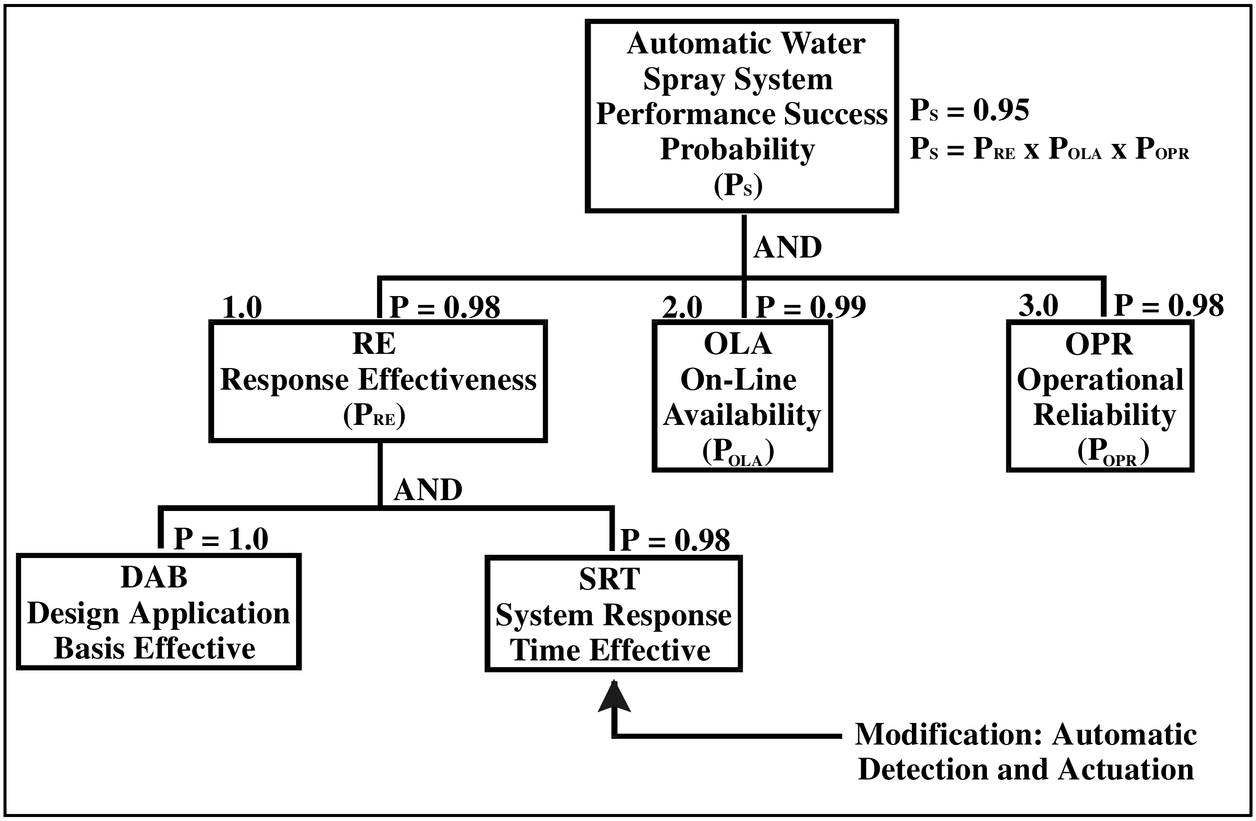


Probability Data Table

DESCRIPTION			PROBABILITY OF FAILURE-ON-DEMAND	REMARKS
I.D.	ITEM	MODE OF FAILURE		
3.1.1.1	Detector D1	Fails to transmit a signal or emergency demand	0.001	Note: Probabilities added for example purposes only
3.1.1.2	Detector D2	Fails to transmit a signal or emergency demand	0.001	
3.1.2	Control Unit and Associated Signaling Wiring	Fails to recognize and respond to detection input signal	0.01	
3.1.3.1	Actuation Solenoid	Fails to operate	0.001	
3.1.3.2	Deluge Valve	Fails to operate	0.01	
3.1.4.1	AC Power	AC power to system fails	0.001	
3.1.4.2	DC Battery	DC Battery backup to system fails	0.001	

From the preceding evaluation, Fig. 8.30 presents a performance success probability of 0.95 based on adding automatic detection and actuation.

Fig. 8.30: Modified Water Spray System Performance Success Probability



The simplicity of the example used in this section helps to convey the methodology involved in quantifying FPS performance upgrades. Once the methodology is understood and the application is consistent, the performance of a wide variety of FPSs with various levels of complexity can be evaluated.

Where manual fire protection systems are being evaluated, the costs associated with automation versus the benefit (i.e., increased performance success rate) must be considered. Cost/benefit analysis is addressed in Sect. 8.5.

8.4 CONSEQUENCE MODIFICATION

The primary consequence modification measures to be focused on in this section include:

1. Modify fire-source intensity via material substitution.
2. Modify the target vulnerability in terms of reducing life safety exposure and business interruption impact.

8.4.1 Material Substitution

Modifying the fire-source intensity can:

- Reduce the source fire heat-release rate and exposure (i.e., heat, temperature, corrosive or toxic smoke concentration, etc.) to the target
- Reduce the potential for secondary ignition and flame propagation and therefore increase the probability of FPS success

In some cases, there is opportunity to substitute a fuel source with a less hazardous alternative, with a lower heat-release rate (HRR) and flame-propagation potential. Some examples include:

- Substituting mineral oil with a silicon-based oil in a transformer
- Replacing a low flash-point solvent in a process with a less flammable solvent
- Using fire resistive or low hazard hydraulic fluids
- Replacing combustible plastic insulated walls with walls having noncombustible insulation
- Substituting a combustible heat transfer fluid with a less hazardous fluid

There are many other examples, but the main point is that material substitution may be a viable option. The following provides a short example related to the evaluation of a substitute material.

The purpose of the following example is to calculate the HRR profiles for two fuels and evaluate the resulting risk effects. HRR calculation is the primary characterization of fire-source intensity. In Chap. 5, Exposure Profile Modeling, the methods for estimating fire-scenario HRR were described. The following is a refresher.

The peak HRR, $\dot{Q}_{peak}$, can be calculated from:

$$\dot{Q}_{peak} = \dot{q}'' \; x \; A_s$$

where $\dot{q}''$ = HRR per unit area (kw/m^2)

A_s = exposed surface area of the fuel (m^2)

The unit area HRR, q, can be calculated from:

$$\dot{q}'' = \dot{m}'' \times H_c \times x_e$$

where $\dot{m}''$ = mass burning rate of fuel, kg/s-m^2
H_c = net heat of combustion of fuel, kJ/kg
x_e = combustion efficiency

Table 8.18 provides comparison of the properties of two generic fluids that are considered source fire fuels.

Table 8.18: Example — Comparison of Properties

PRIMARY PROPERTIES OF INTEREST	EXISTING FUEL	SUBSTITUTE FUEL	REFERENCES
1. Heat of combustion, H_C (kJ/kg)	40,000	28,000	↑ LIST REFERENCES AND REMARKS ↓
2. Mass burning rate, M_b (kg/m^2-s)	.035	.018	
3. Flash point/auto ignition temp	120°F/350°F	168°F/700°F	
4. Fire growth rate	Fast	Moderate	
5. Incident radiant heat flux required for ignition (kw/m^2)	8 – 10	18 – 21	
6. Products of combustion, corrosive, toxic	—	Similar	
7. Extinguishing difficulty	—	Less *	
8. Clean up, environmental issues	—	Similar	
9. Feasibility of substitution from technical perspective	—	Can do	
10. Estimated cost of upgrade	—	$20,000.00**	

Comments:
* Because of the higher flash point and lower HRR, fire suppression should be quicker and easier.
** Based on engineering evaluation and consultation with the manufacturers, seals in the existing fluid transfer system will have to be replaced at an approximate cost of $20,000. Annual maintenance costs would be the same.

The unit HRR $\left(\dot{q}\right)$ for the existing fuel is:

$$\dot{q} = \dot{m} \times H_c \times x_e$$

Assume: $x_e = 1.0$

$$\dot{q}'' = \left(.035\, kg/m^2 - s\right)\left(40{,}000\, kj/kg\right)(1.0)$$

$$\dot{q}'' = 1{,}400\, kw/m^2$$

For the substitute fuel, the unit heat release rate is:

$$\dot{q}'' = \left(.018\, kg/m^2 - s\right)\left(28{,}000\, kj/kg\right)(1.0)$$

$$\dot{q}'' = 504\, kw/m^2$$

Based on this first calculation, the substitute fuel exhibits a 64% lower unit HRR than the existing fuel.

The surface area, A_s, now becomes the next calculation issue, as the total peak HRR is equal to:

$$\dot{Q}_{peak} = \dot{q}\; x\; A_s$$

The exposed surface area can have a major effect on the total HRR potential. Table 8.19 provides an example of the differences in the calculated HRR for two diked fluid containment areas:

Table 8.19: Example – HRR Versus Diked Area

FUEL SOURCE	10FT X 10FT DIKED AREA	8FT X 8FT DIKED AREA
Existing fuel $\dot{q}'' = 1{,}400\, kw/m^2$	$\dot{Q} = 13{,}023 kw$	$\dot{Q} = 8{,}355 kw$
Substitute fuel $\dot{q}'' = 504\, kw/m^2$	$\dot{Q} = 4{,}688 kw$	$\dot{Q} = 3{,}000 kw$

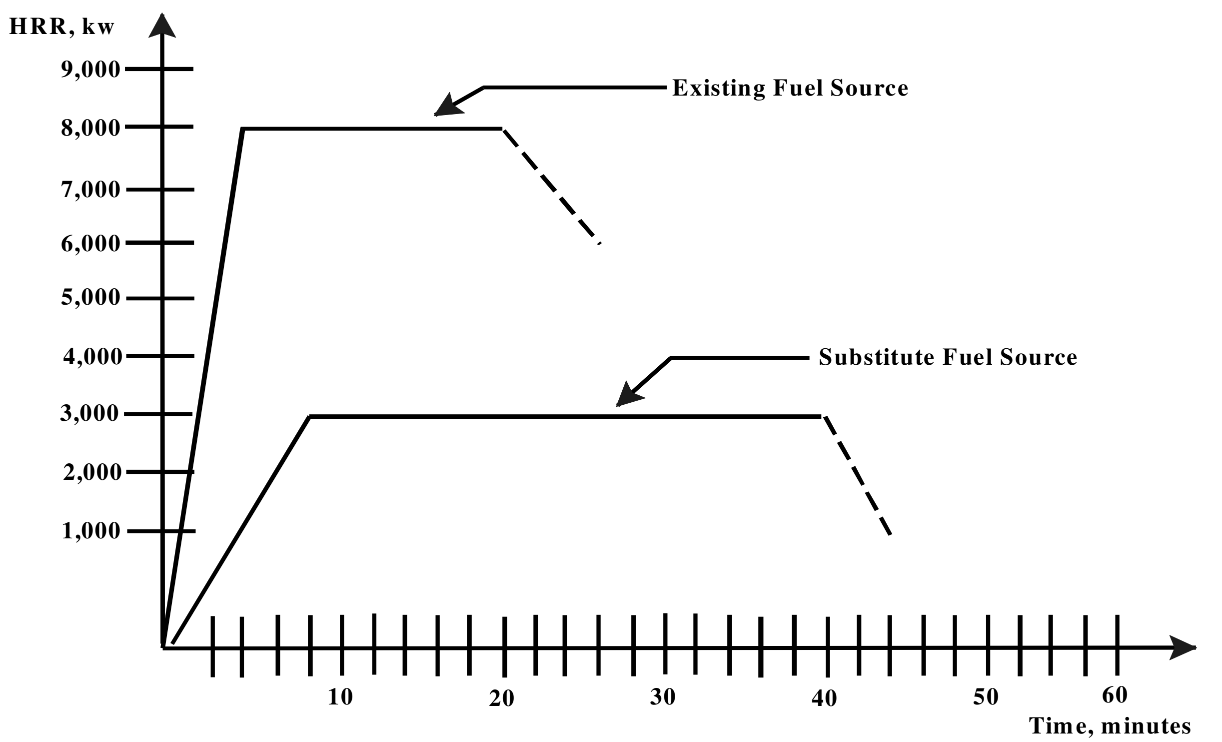
Fire growth and burning duration calculations were described in Chap. 5. For the example existing fuel, a fast, t^2, fire-growth rate was assumed. For the substitute fuel, a moderate, t^2 fire growth rate was assumed. To calculate the time to unmitigated burn-out, 600 lb of fuel was assumed. The results are shown in Table 8.20.

Table 8.20 Estimating Time to Reach Peak HRR and Fuel Burn-Out Time

FUEL SOURCE PEAK HRR	TIME TO REACH PEAK HRR	TIME TO UNMITIGATED BURN -OUT
Existing fuel $\dot{Q} = 8{,}335kw$	t = 216 seconds (3.6 min) — fast fire growth rate assumed	t = 22 min Assumed 600 lb of fuel
Substitute fuel $\dot{Q} = 3{,}000kw$	t = 260 seconds (4.3 min) — moderate fire growth rate assumed	t = 42 min Assumed 600 lb of fuel

Figure 8.31 provides an HRR profile comparison between the existing fuel and substitute fuel source.

Fig. 8.31: Unmitigated HRR Profile for Existing and Substitute Fuel Sources



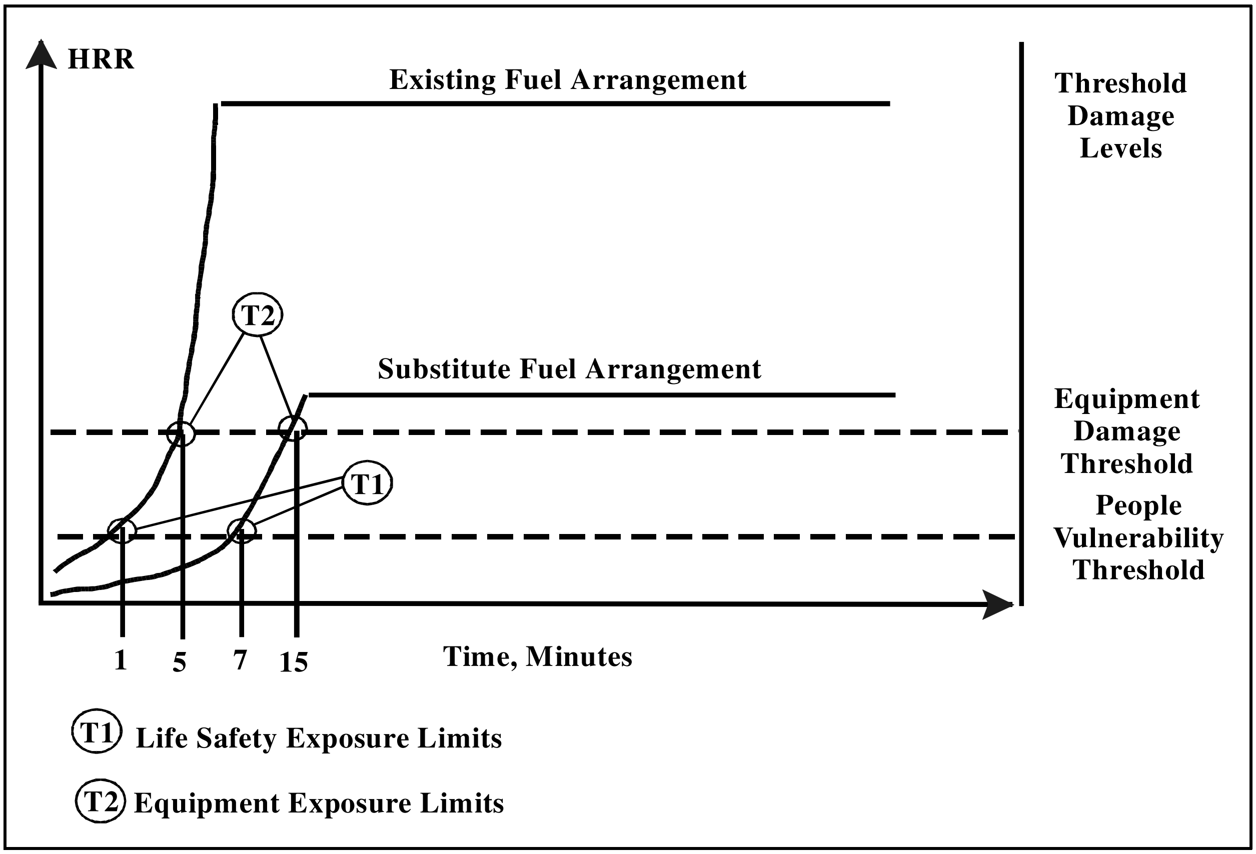
Once the HRR for the initial source fire is estimated, other target exposure parameters can be calculated:

- Fire exposure levels
  - — Radiant heat versus distance
  - — Convective heat and temperature
    - – ceiling jet region
    - – plume region

  – smoke layer
- — Time to secondary ignition and fire propagation
- — Smoke-layer depth
- — CO/O_2 conditions
- — Corrosive gas species
- FPS actuation times of
- — Detection devices
- — Sprinkler systems
- — Fuse-link-operated vents, doors, emergency controls.

Figure 8.32 provides an example of fire-exposure level versus time for the existing and modified fuel arrangement.

Fig. 8.32: Example Generic Graph — Fire-Exposure Level Versus Time



Based on the assumed values in Fig. 8.32, the exposure-level time limits are:

Fuel arrangement	(T1) Life safety exposure limit	(T2) Equipment exposure limit
Existing fuel	1 min	5 min
Substitute fuel	7 min	15 min

People evacuate safely — no injuries

$$T_1 < \text{Time}_{\text{Detection}} + \text{Time}_{\text{Alarm Notification}} + \text{Time}_{\text{Evacuation}}$$

Equipment – no major damage

$$T_2 < \text{Time}_{\text{Detection}} + \text{Time}_{\text{Fire System Response}} + \text{Time}_{\text{Fire Suppression}}$$

Figure 8.33 presents an example event tree for the existing fuel source with the associated time line. Since evacuation of personnel would have to occur within 1 min, the probability of success for detection and evacuation is low, P = 0.05. Also the probability of fire-suppression success at 5 min is low.

In comparison, Fig. 8.3.4 presents an example event tree for the substitute fuel source. Note the difference in the time line. Because of the lower exposure level time limits, the probability of detection and fire-suppression success are much higher, thus lowering the life safety and equipment damage risk.

If we assume a Level 3 life safety exposure has an equivalent dollar value of $1,000,000, and a Level 3 equipment exposure is valued at $500,000, the difference in risk for this exposure level is:

	LIFE SAFETY EXPOSURE RISK	EQUIPMENT DAMAGE EXPOSURE RISK
Existing fuel source:	$ 57,000 (1)	$ 28,500 (2)
Substitute fuel source:	$ 1,000 (3)	$ 500 (4)
Change in annualized risk from using substitute fuel:	$ 56,000	$ 28,000

(1) 0.057 x $1,000,000 (2) 0.057 x $500,000
(3) 0.001 x $1,000,000 (4) 0.001 x $500,000

Note: Likelihoods 0.057 and 0.001 are from branch line 4 in Figs. 8.33, 8.34

As an initial observation, with the large potential annualized risk reduction of $84,000, versus the estimated cost of $20,000 to upgrade, the change to the substitute fuel appears very cost-effective.

Fig. 8.33: Example Tree – Existing Fuel Source

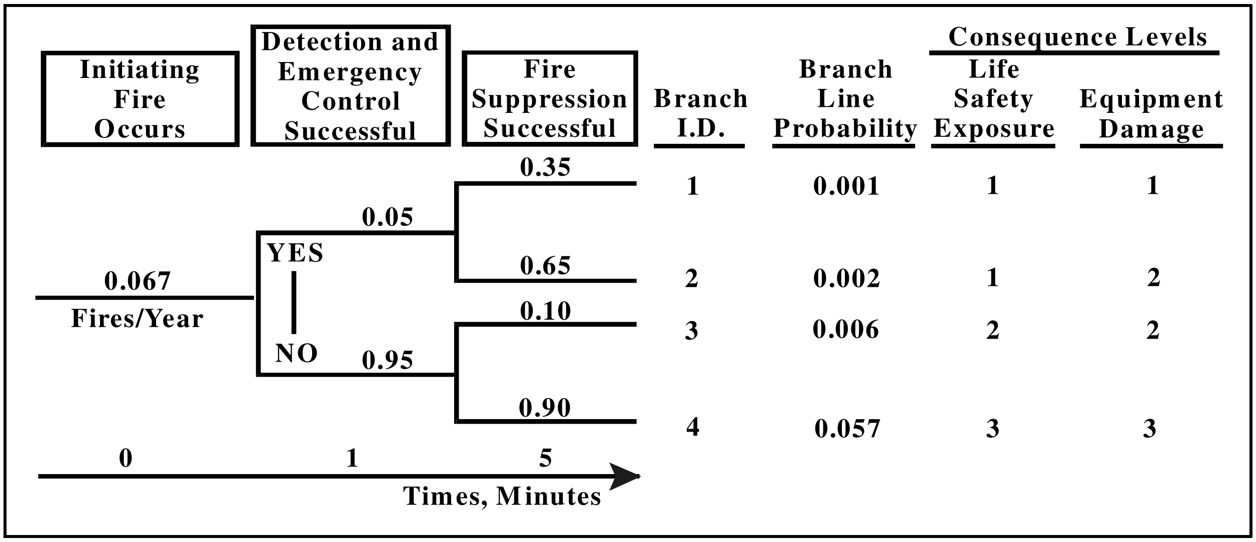
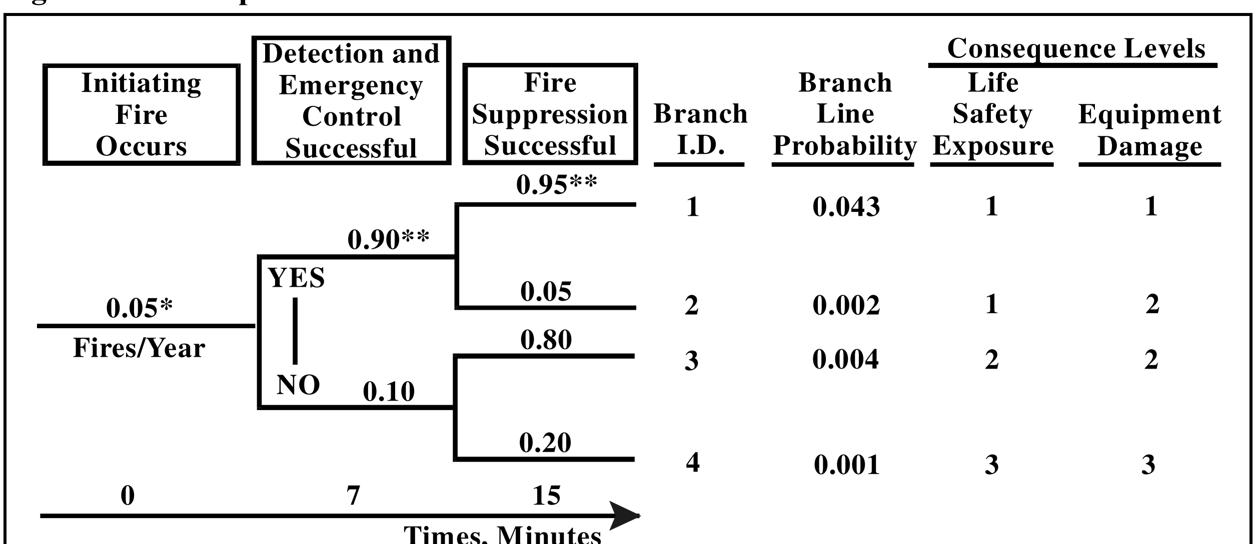


Fig. 8.34: Example Event Tree – Substitute Fuel Source



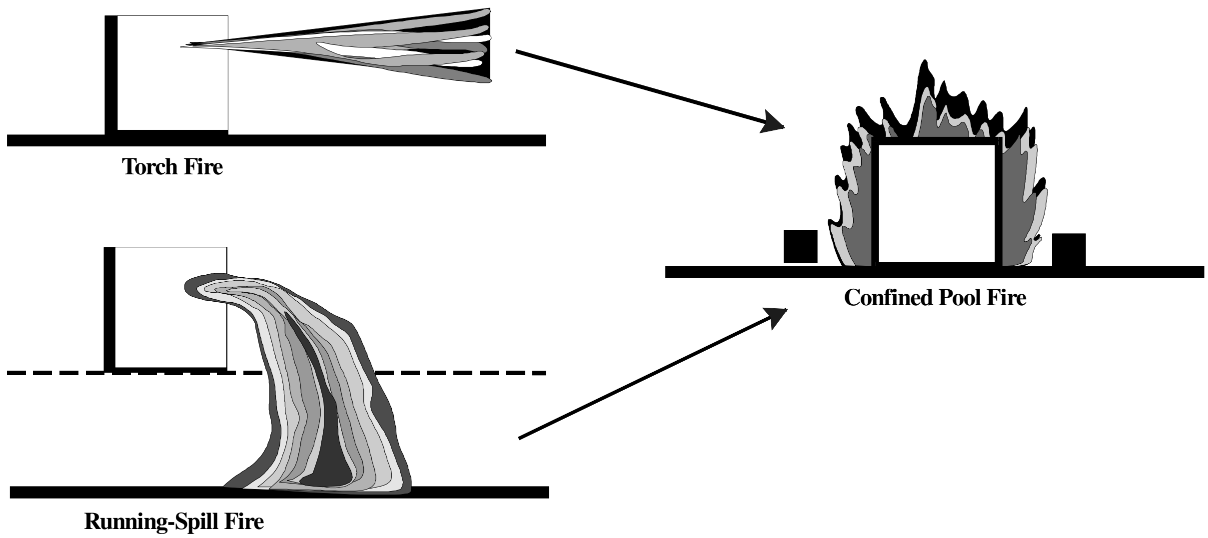
* Because of much higher ignition temperature of the substitute fuel, the initiating fire event likelihood was reduced 20%.

** The performance success of the detection and emergency control system and fire suppression system, improves due to the increased time limits for response (i.e., 7 to 15 minutes versus 1 to 5 minutes for the existing fuel source).

Other source-intensity-modification considerations for combustible fluids can include:

- If technically feasible, provide design features to channel releases of combustible fluids into a confined-pool, two-dimensional fire configuration, accessible for quick extinguishment, as show in Fig. 8.35.
- Provide diking.
- Evaluate inventory reduction.

Fig. 8.35: Torch Fire, Running-Spill Fire Versus a Confined-Pool Fire



NOTE: The fire dynamics of torch, spill, and pool fires are discussed in Chap. 5, Exposure Profile Modeling

Dikes limit the spread of liquid during a release and slow down the evaporation rate by reducing the pool area. The evaporation rate can also be reduced by making the dike from insulating concrete. For a dike to be effective, it should be as small as possible (i.e., minimize the pool surface area) and yet be able to accommodate the entire volume of liquid. In addition, its shape should be designed to prevent the liquid from surging over the sides. The walls should be far enough away from the vessel so that a jet release does not overshoot it, but they should not be so high that they will hinder firefighting.

The primary objective when reducing inventories should be to reduce the quantity of hazardous materials so that the potential consequences of a release are greatly reduced, or even eliminated. Inventories can be reduced by the following approaches:

- Reduce the quantity of hazardous materials in storage and used in processing. In many instances, it has been possible to operate plants with considerably lower quantities of raw materials and intermediate products than was proposed in the original design.
- Modify the process to produce the hazardous materials as a small quantity of intermediate material, eliminating the need to store large quantities of the dangerous materials.

- If feasible switch from a batch to a continuous-reaction system that will allow for lower inventories.

Combustible Solids

In some cases, use and storage of combustible solids and storage arrangements can be changed to modify the HRR profile and improve the probability of FPS suppression success. Primary factors that can affect fire growth, HRR, and suppression success include:

- Packaging material alternatives
- Exposed surface area reduction
- Storage height reduction
- Increased separation between storage
- Changing location of storage
- Storage stability modification
- Ventilation influences
- Fire suppression system response time and penetration

8.4.2 Modify Life Safety Exposure Levels

Evaluating life safety exposure modification generally involves the following two steps:

1. For the existing risk levels, identify and understand the life safety issues that contribute to the life safety exposure levels.
2. Evaluate the quantitative change in life safety exposure levels for various improvement strategies and compare with the established Life Safety Risk Tolerance Profile.

Figure 8.36 provides an example event tree that presents an assessment of existing life safety exposure levels. In this event tree, there is an independent, area wide fire detection and alarm system to notify people and a localized automatic suppression system with a separate detection and actuation system.

Fig. 8.36: Example Event Tree Focusing on Life Safety Exposure Levels

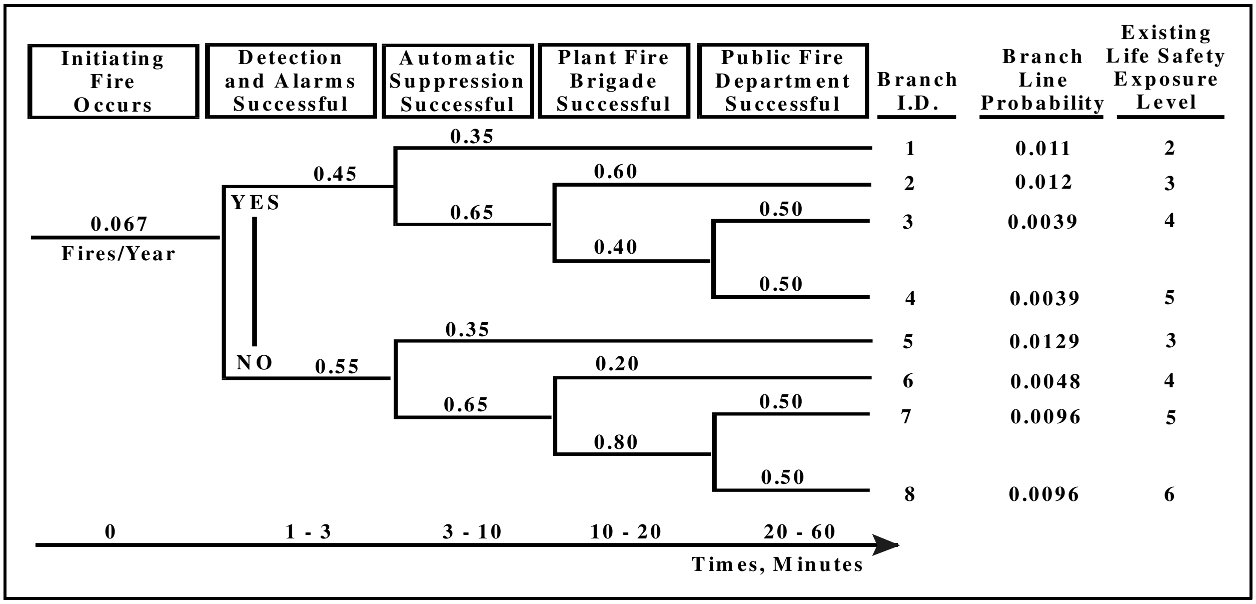


Table 8.21 provides an example list of life safety exposure categories used in this example.

Table 8.21: General Example of Life Safety Exposure Categories

LIFE SAFETY EXPOSURE	GENERAL DEFINITION
1 – Low	First aid — (one person, primarily smoke-related exposure)
2 – Moderate	Moderate burn injury potential may require hospital treatment (one person)
3 – Heavy	Severe burn potential requiring hospital treatment (1–2 people)
4 – High	Potential for multiple injuries, single death on site
5 – Very High	Potential for 2–10 fatalities on site
6 – Extremely High	Potential for multiple injuries or single death — OFF-SITE
7 – Catastrophic	Potential for multiple fatalities — OFF-SITE

Table 8.22 describes the Fig. 8.36 event tree incident outcomes, life safety exposure levels, and identified life safety deficiencies. Based on an engineering site survey, the last column in this table lists life safety problems, which include:

- Contractor training in terms of alarm and evaluation response is unsatisfactory.
- Emergency lighting to aid exiting is insufficient.
- Fire bridge response (which the plant relies heavily on) is inadequate.
- Fire department pre-planning is not satisfactory.
- Evacuation alarm notification and instructions are insufficient based on the fire propagation time line.
- Fire department does not have a formal site and evacuation plan related to chemical fire and explosion situations.

Table 8.22: Summary of Life Safety Deficiencies Related to Fig. 8.36 Event Tree

BRANCH I.D.	INCIDENT OUTCOME	LIFE SAFETY EXPOSURE LEVEL	DEFICIENCIES
1	Detection within 3 min, automatic suppression within 10 min	2; Low exposure to employees. Moderate exposure to contractors in area	Alarm and evacuation training for contractors is not satisfactory
2	Detection within 3 min, fire brigade suppression within 20 min	3; With automatic suppression unsuccessful, heat and smoke would create a moderate to high exposure	Exits are adequate. However, this is a windowless building with insufficient emergency lighting
3	Detection within 3 min. Automatic suppression and fire brigade unsuccessful. Public fire department successful within 60 minutes in confining-fire to building of fire origin	4; Without fire brigade success within 20 min, the building could start to lose structural integrity creating a high exposure level	Fire brigade staffing levels and training are not adequate
4	Detection within 3 min. Fire remains uncontrolled at 60 min. Assumes fire department arrives in time to protect exposed chemical storage building.	5; If fire is not controlled within 60 min, it could spread to adjacent chemical storage building, creating a very high exposure level	Fire department pre-planning is not satisfactory. Plant has not run training drills for plant evacuation
5	Fire is NOT detected within 3 minutes. Automatic Suppression system is independent of detection system and is successful within 10 min	1; Moderate exposure to employees and contractors	Facility does not have a back-up PA system to assist in evacuation and instruction should the existing automatic detection system fail
6	Fire is NOT detected within 3 min, and automatic suppression is unsuccessful. Fire brigade provides control and suppression	2; High exposure to employees, contractors, and responding fire brigade members	See Branch I.D. (2)(3)(5)
7	Fire is NOT detected within 3 min. Automatic suppression and fire brigade unsuccessful. Assumes delayed fire department notification; however, fire department is able to provide exposure protection to chemical storage building	3; Very high exposure due to potential loss of structural integrity of building at 20–30 min	See Branch I.D. (3)(4)(5)
8	Uncontrolled fire situation spreads to adjacent chemical storage building	4; Extremely high. If the chemical storage building becomes involved, an explosion potential exists that could have off-site consequences	Fire department does not have a formal public evacuation plan for this scenario

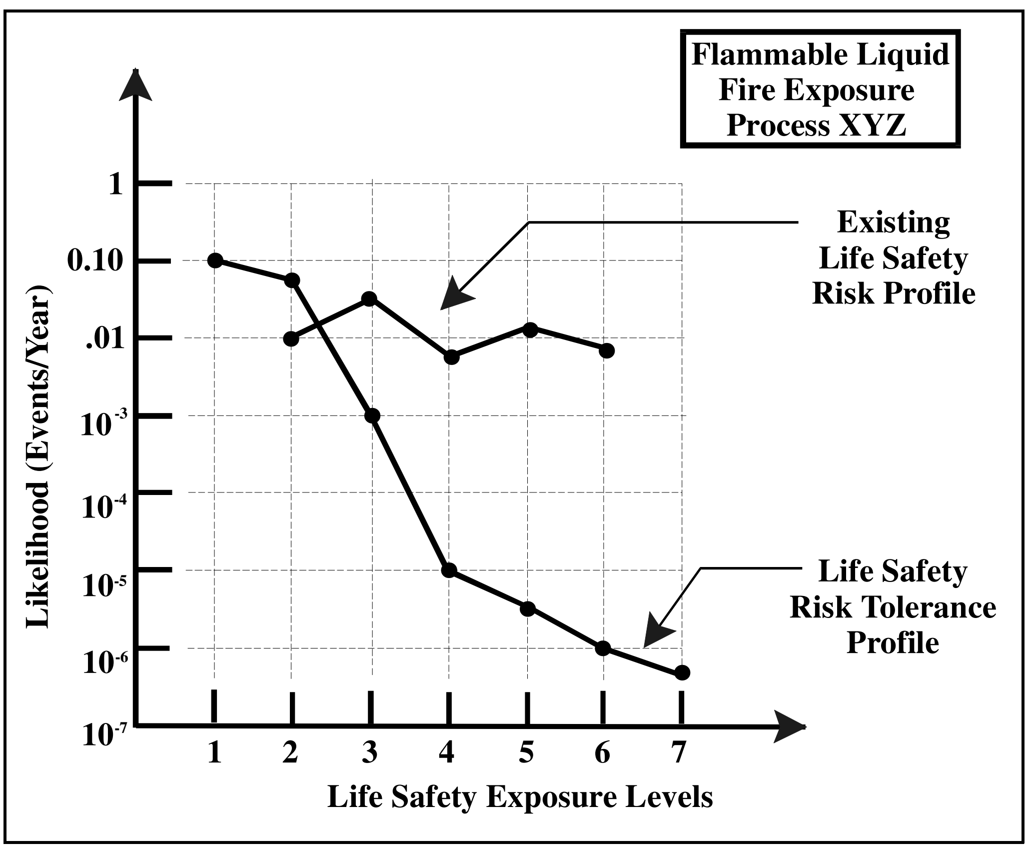
Table 8.23 relates the likelihood (calculated from the event tree in Fig. 8.36) of reaching various life safety exposure levels.

Table 8.23: Existing Likelihood of Reaching Life Safety Exposure Levels

BRANCH I.D.	LIFE SAFETY EXPOSURE LEVEL	LIKELIHOOD OF REACHING EXPOSURE LEVEL
1	2	0.011
2, 5	3	0.025
3, 6	4	0.0087
4, 7	5	0.0135
8	6	0.0096

Figure 8.37 plots the existing life safety exposure profile. As evident in this figure, the existing life safety risk exceeds the established Life Safety Risk Tolerance Profile; therefore, risk reduction evaluation is warranted.

Fig. 8.37: Existing Life Safety Risk Profile



Based on the existing Life Safety Risk Profile and the deficiencies noted in Table 8.22, assume the Plant decides to evaluate the following improvements:

- Improve contractor alarm and evacuation training
- Provide additional emergency lighting
- Upgrade fire brigade staffing and training
- Work with the public fire department to improve pre-planning, plant evacuation drills, and public notification

Based on engineering assessment and judgement, the improvements warrant the reduction of life safety exposure of one level (e.g., implementing a quality contractor training program reduces the exposure level from 2 to 1).

In addition, the Plant decides to upgrade the performance of the automatic detection and alarm notification system and improve the performance of the automatic suppression system. The modified event tree for these assumed upgrades is shown in Fig. 8.38.

Fig. 8.38: Modified Event Tree

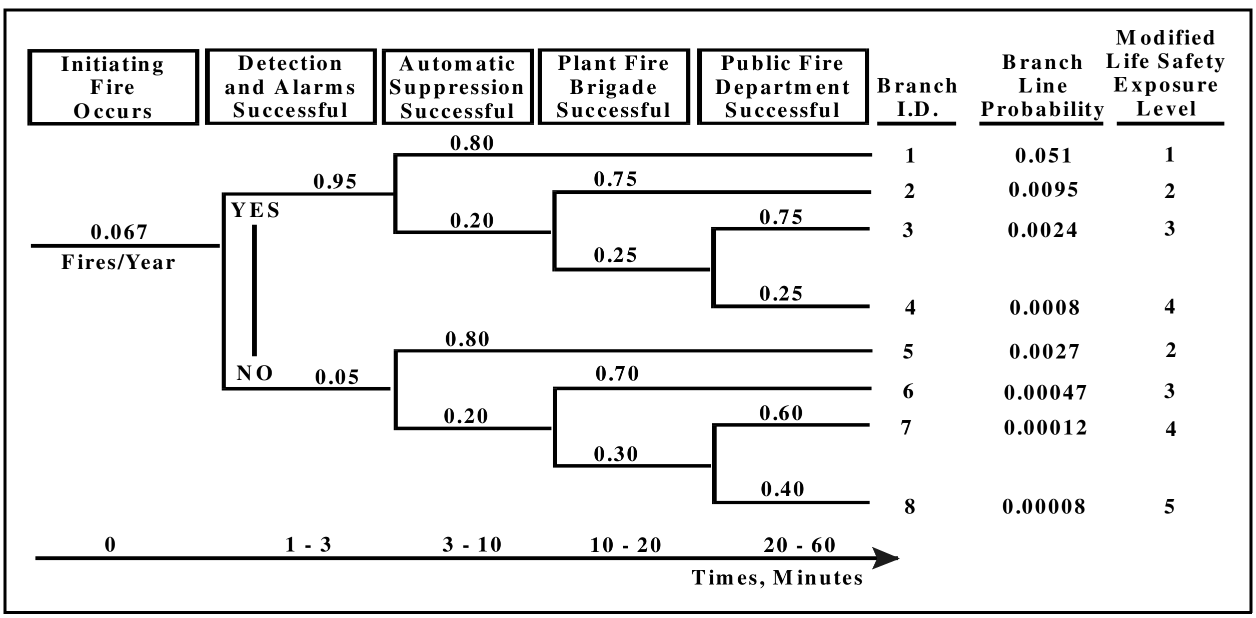
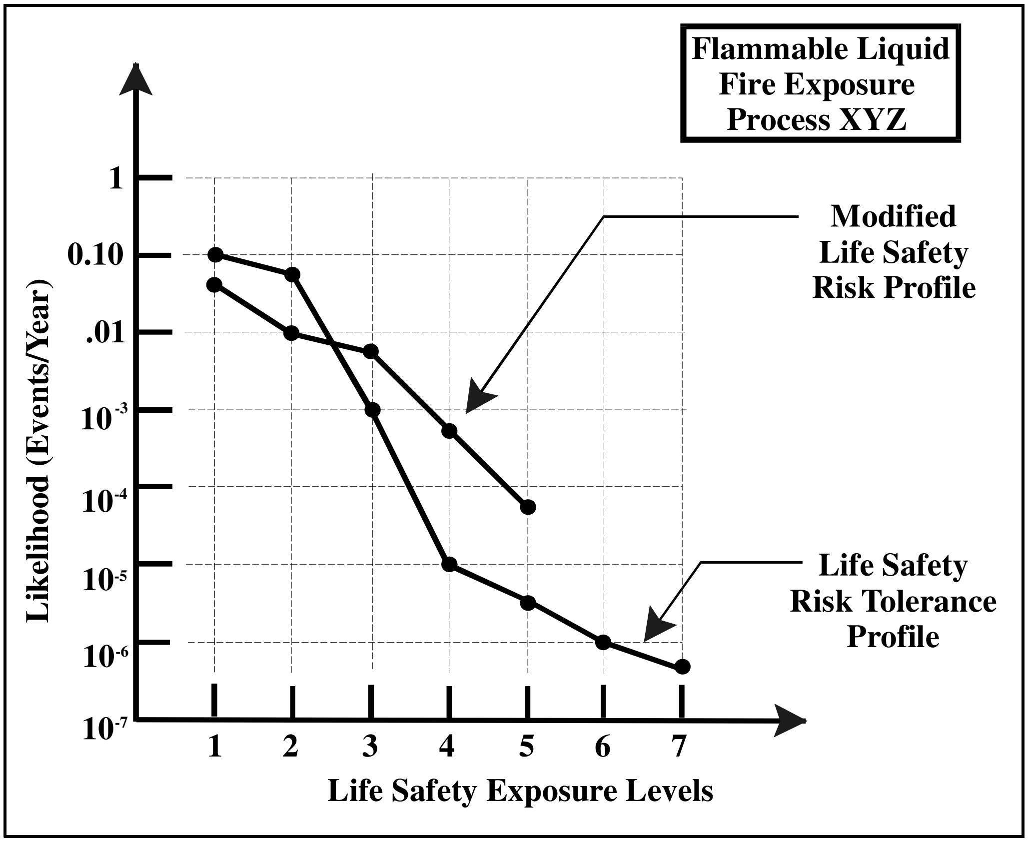


Figure 8.39 presents the modified life safety risk profile. Evident in this figure is that the modified profile still slightly exceeds the life safety risk tolerance profile. At this point, the plant may want to evaluate reducing the initiating fire event likelihood. The existing likelihood of 0.067 indicates the likelihood of having the defined initiating fire potential is 1 fire per 15 years. The plant needs to evaluate fire prevention options to reduce this likelihood to further modify the profile in Fig. 8.39.

Using this type of event tree risk evaluation allows assessment of alternatives to reduce the life safety exposure, upgrade fire protection system performance, and reduce the initiating fire event. The next consideration would be the cost/benefit analysis of this alternative to meet risk tolerance objectives. Cost/benefit analysis is addressed in Sect. 8.5.

Fig. 8.39: Modified Life Safety Risk Profile



8.4.3 Modify Business Interruption (BI) Impact Levels

Evaluating BI exposure modification generally involves the following steps:

1. Identify and understand the issues and factors that contribute to the existing BI exposure levels.
2. Evaluate the quantitative change in potential BI exposure levels for various BI reduction strategies and compare with the established BI Risk Tolerance Profile.

Figure 8.40 provides an example event tree focusing on BI exposure levels. Again, this event tree assumes an independent area wide fire detection alarm system and a localized automatic suppression system with a separate detection and actuation system.

Fig. 8.40: Example Event Tree Focusing on BI Exposure Levels

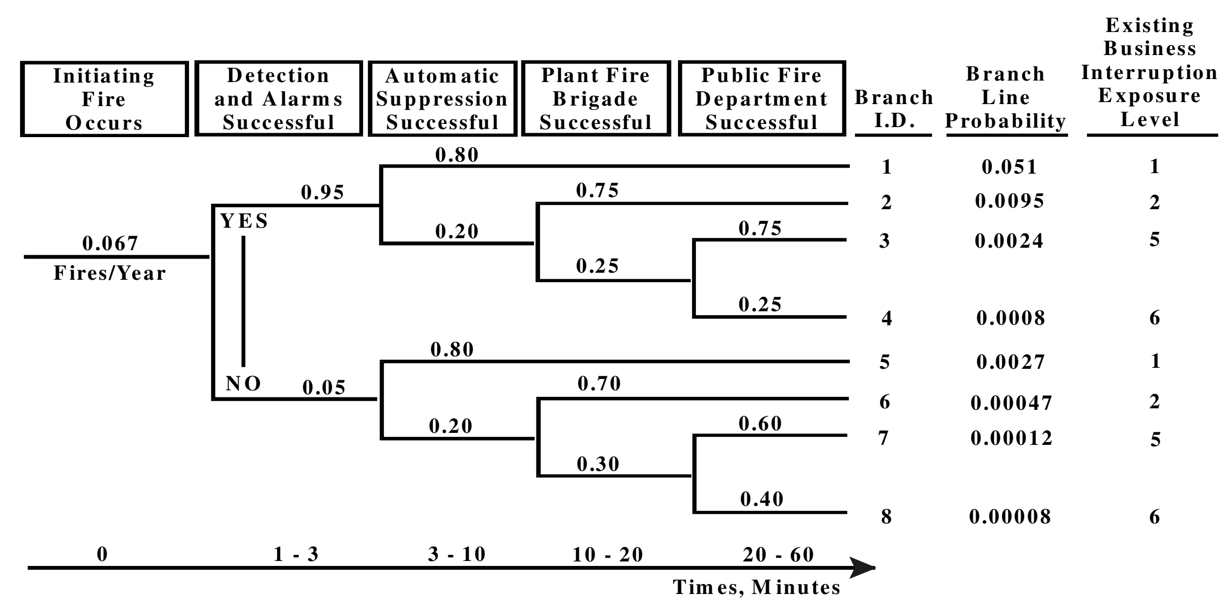


Table 8.24 presents an example of establishing BI exposure categories.

Table 8.24: Example of BI Categories

BI LEVELS	PRODUCTION DOWNTIME RANGE	AVERAGE PRODUCTION DOWNTIME, DAYS
1 – Slight	0 – 1 days	0.5
2 – Light	1 – 10 days	5
3 – Moderate	10 – 30 days	20
4 – Heavy	30 – 90 days	60
5 – Major	90 – 270 days	180
6 – Critical	270 – 360 days	315
7 – Total	1 – 2 Years	Use maximum expected

Table 8.25 relates the likelihood (calculated from the event tree in Fig. 8.40) of reaching various BI exposure levels.

Table 8.25: Existing Likelihood of Reaching BI Exposure Levels

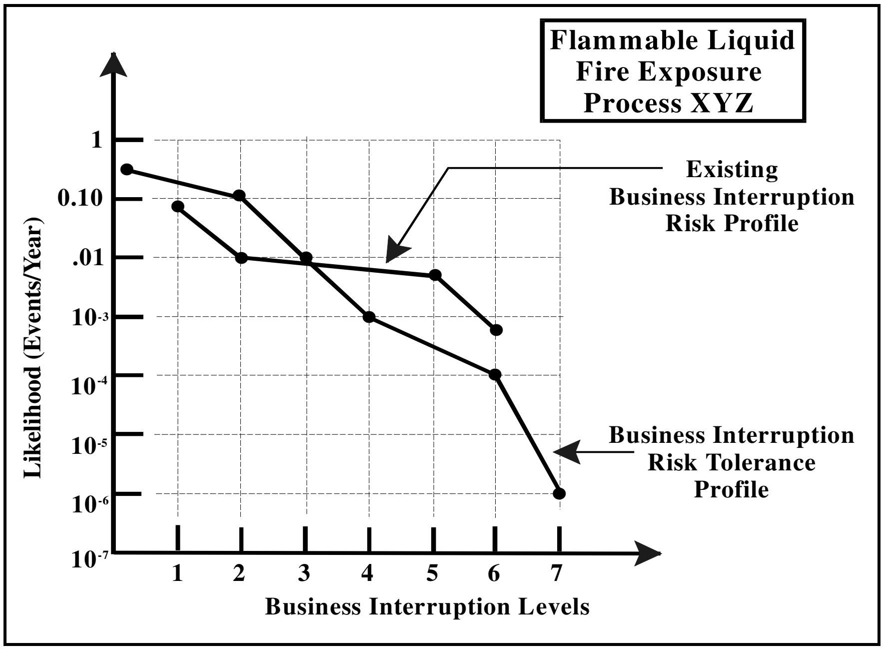
BRANCH I.D.	BUSINESS INTERRUPTION EXPOSURE LEVELS	LIKELIHOOD OF REACHING EXPOSURE LEVEL	DESCRIPTION	DEFICIENCIES / REMARKS
1,5	1	0.054	Less than 1 day downtime for cleanup	None; planning in place for minor fires
2,6	2	0.0099	Estimated 5–7 days downtime for cleanup and repair	None; planning in place for moderate fire exposures
3,7	5	0.0025	Could be down 3–4 months for major equipment repairs	Spare parts program is deficient
4,8	6	0.00088	Could be down 10–12 months for equipment replacement and structural repair	Contingency planning is not adequate

The last column in Table 8.25 provides a listing of general deficiencies that includes:

- Spare parts program (i.e., ability to expedite on-site repair and replacement of production equipment) is deficient.
- Contingency planning (i.e., ability to meet customer orders and contracts by having contingency plans with other company-owned plant facilities or outsourcing contracts) is deficient.

It should be noted that BI analysis for automated industrial production operations or chemical processes can be a complex evaluation and usually involves many variables, issues, and cost alternatives. The purpose of this example is to present the approach for using BI categories applied within an event tree analysis to provide a first-order comparison of existing BI risk versus the established BI risk tolerance profile. For this example, Fig. 8.41 plots the existing BI exposure profile. As presented in this figure, the existing BI risk profile exceeds the established BI risk tolerance profile; therefore, BI risk reduction evaluation is warranted.

Fig. 8.41: Existing BI Risk Profile



The event tree in Fig. 8.42 presents an example of modified BI exposure levels based on engineering review assessment and judgement. This assumes improvements in the plant's spare part program and contingency planning to meet customer orders during an extended plant downtime from a major fire incident. This type of evaluation allows review of various alternatives to reduce BI risk from various fire events.

Fig. 8.42: Modified Event Tree

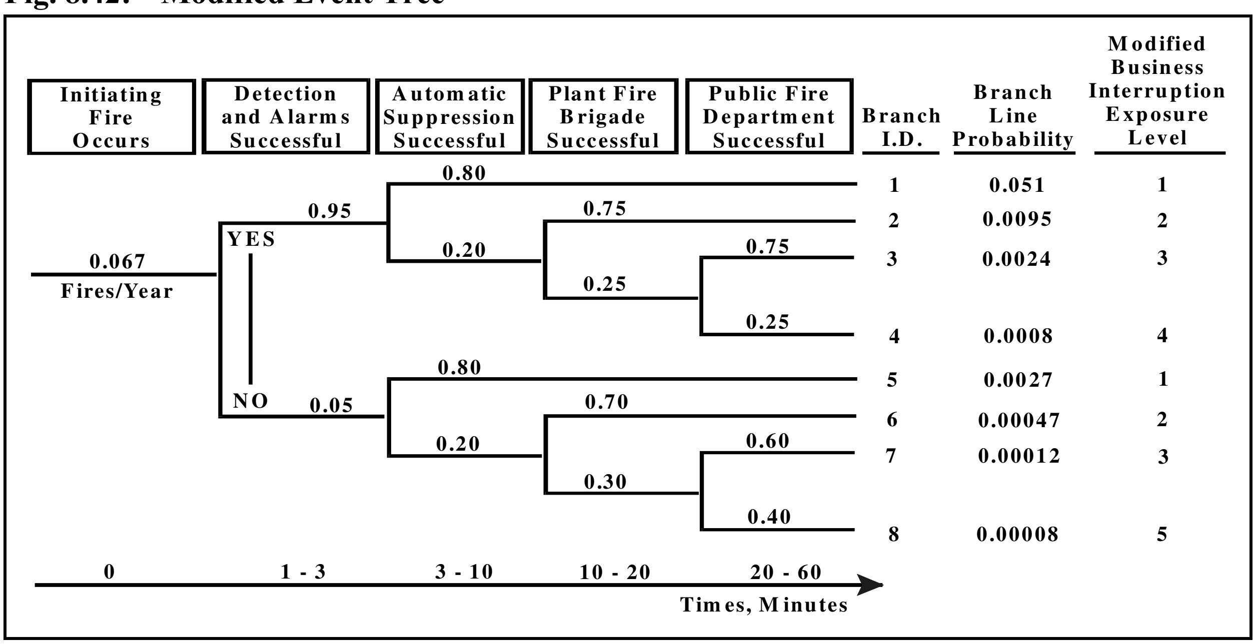
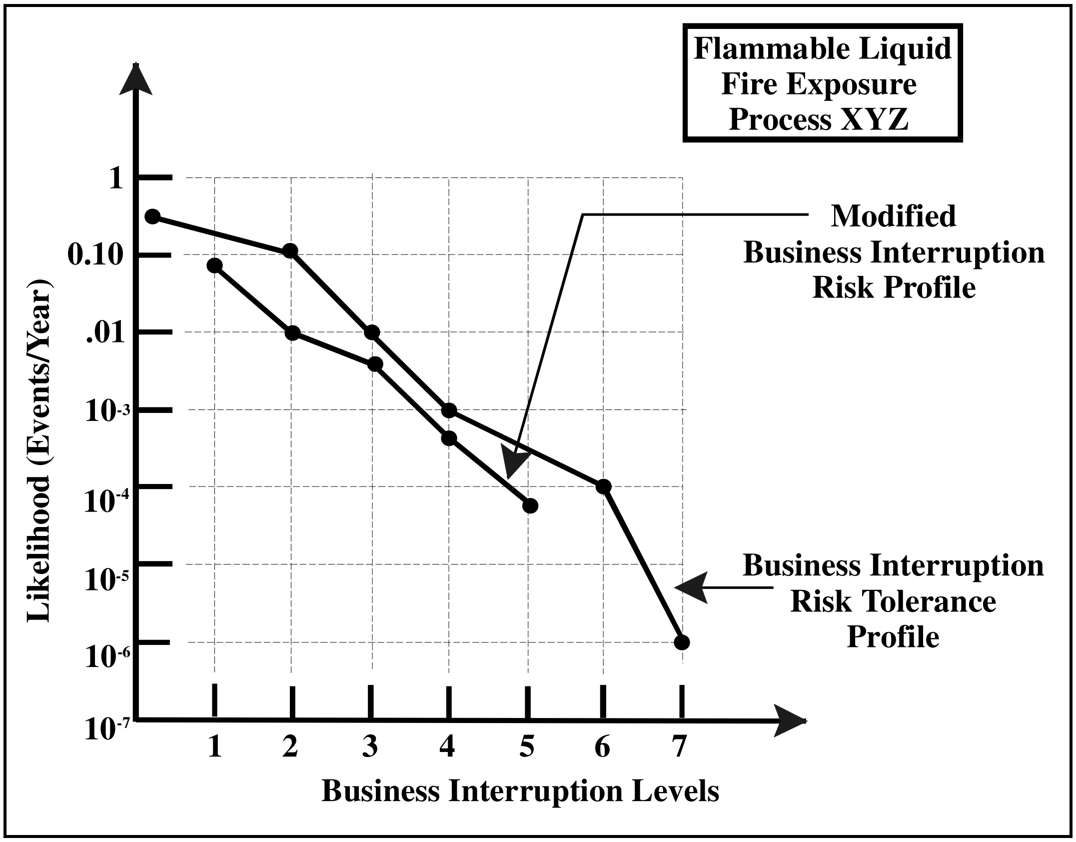


Figure 8.43 presents a comparison (based on the modified event tree in Fig. 8.42) of the modified BI risk profile with the assumed improvements versus the established risk tolerance profile. The next consideration would involve the cost-effectiveness of the proposed improvement alternatives. Cost/benefit analysis is discussed in the next section.

Fig. 8.43: Modified BI Risk Profile



8.5 COST/BENEFIT ANALYSIS OF RISK REDUCTION ALTERNATIVES

The cost/benefit analysis process described in this section consists of:

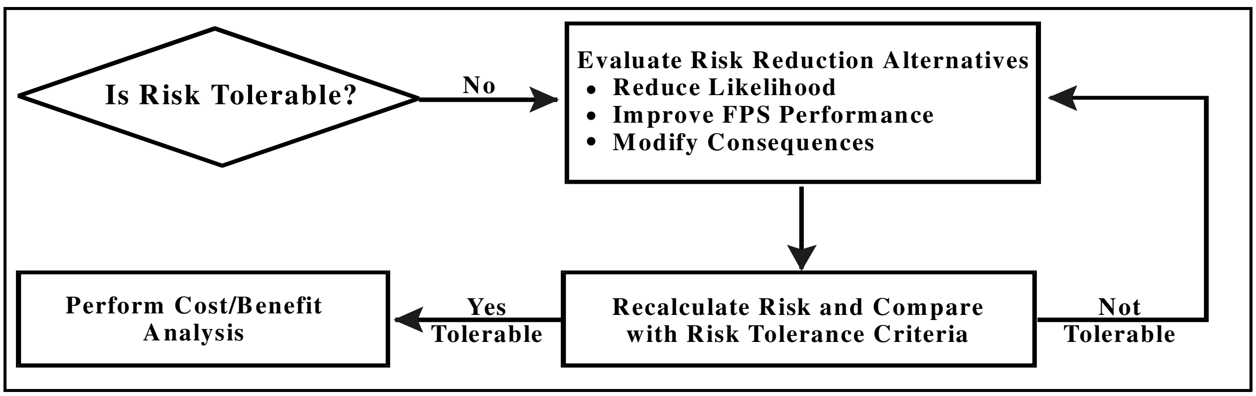
- Quantification of risk reduction alternatives
- Cost analysis for selected strategies
- Ranking of strategies by risk reduction/cost ratios
- Decision analysis

8.5.1 Quantification of Risk Reduction Alternatives

As presented in Fig. 8.44 and described in the previous sections, there are three primary ways to reduce fire risk:

- Reduce the initiating event likelihood
- Improve FPS performance
- Modify the consequence levels

Fig. 8.44: Risk Reduction Evaluation Process

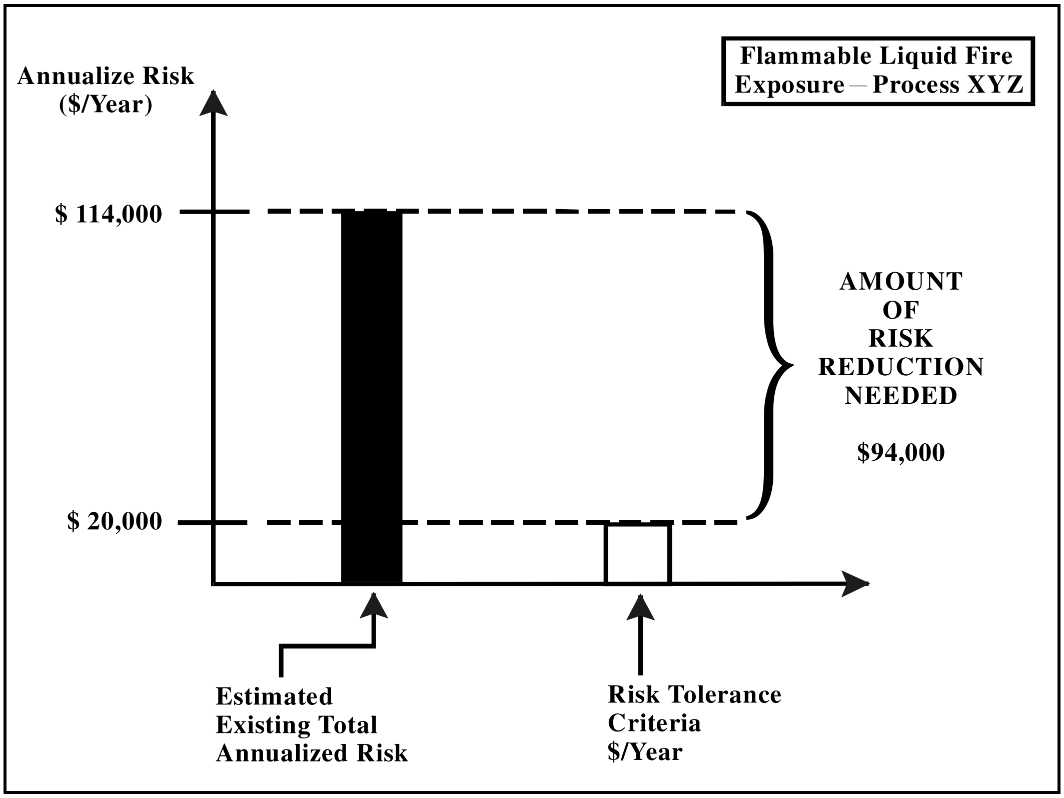


After the risk analysis team has identified and screened various risk reduction alternatives, the next step is to quantify the modified risk related to each alternative or set of alternatives (strategies) and compare to the risk tolerance criteria. Alternatives that can meet the risk tolerance criteria must then be further evaluated in terms of cost/benefit analysis.

How Much Risk Reduction is Needed?

Figure 8.45, which is based on the example event tree in Fig. 8.46, presents an example graphical depiction of the estimated existing risk versus the preestablished risk tolerance criteria. In this example, the annualized risk reduction needed is $94,000. The annualized risk is an "aggregate" monetary equivalent that usually includes property damage, BI, life safety exposure, fire-related environmental exposure, and company image. The establishment of risk tolerance criteria is addressed in Chap. 2.

Fig. 8.45: Example Depiction of Existing Annualized Risk Versus Risk Tolerance



Criteria

The example event tree in Fig. 8.46 presents at the bottom the primary risk reduction measures that can be evaluated:

- Reduce initiating event likelihood,
- Improve FPS performance.
- Modify consequence levels.

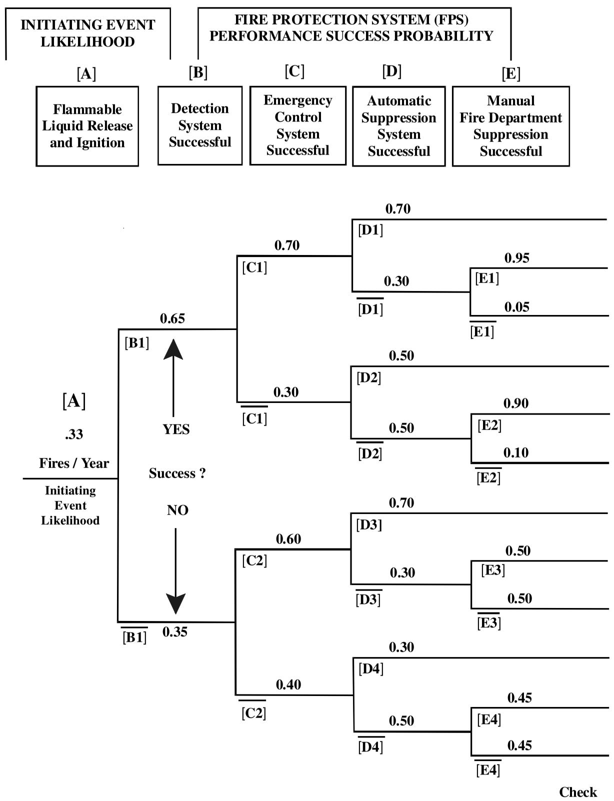
Columns [H] [I] [J] in Fig. 8.46 represent consequence levels. Column [K] represents the conversion of consequence levels to equivalent monetary values.

The last column, [L], calculates the existing total annualized risk, which is a product of the branch line probability [F] and the equivalent monetary value [K].

The initial approach for evaluating risk reduction effects is to perform a “What-If” type of analysis.

Fig. 8.46: Example Fire Risk Event Tree

SOURCE → PATHWAY (MODIFIERS) → TARGET



BRANCH ID	[F] BRANCH LINE PROBABILITY	[G] INCIDENT OUTCOME	[H] PROPERTY DAMAGE: BUILDING DAMAGE	[H] PROPERTY DAMAGE: EQUIPMENT DAMAGE	[H] PROPERTY DAMAGE: STOCK DAMAGE	[I] PRODUCTION DOWN TIME	[J] LIFE SAFETY EXPOSURE	[K] AGGREGATE EQUIVALENT MONETARY VALUE, $	[L] [L] = [F] × [K] ANNUALIZED F&E RISK $ / YEAR
1	0.105	G 1	1	1	1	1	0	5k	526
2	0.043	G 2	1	2	2	1	0	10k	428
3	0.002	G 3	3	3	3	3	0	1M	2,252
4	0.032	G 1	1	2	1	1	0	7k	225
5	0.028	G 2	2	2	2	2	0	25k	724
6	0.003	G 3	3	4	3	3	1	2M	6,435
7	0.049	G 1	1	2	1	1	0	7k	340
8	0.01	G 2	2	2	2	2	0	25k	260
9	0.01	G 3	3	3	3	3	3	2.5M	25,987
10	0.023	G 1	1	2	2	1	0	10k	231
11	0.01	G 2	2	2	2	2	0	25k	260
12	0.013	G 4	4	5	4	4	4	6M	76,230
Check	0.33								$ 113,898 Total Annualized Risk; $/Year

EXPOSURE PROFILE / CONSEQUENCE LEVELS — RISK ESTIMATIONS

TIME LINE: 1 - 3 | 2 - 5 | 5 - 10 | 10 - 30 minutes

REDUCE INITIATION EVENT LIKELIHOOD — IMPROVE FIRE PROTECTION SYSTEM PERFORMANCE — RISK REDUCTION OPPORTUNITIES — MODIFY CONSEQUENCE LEVELS

What-If Analysis

Use of a computer spreadsheet program such as Excel by Microsoft to develop event tree models and documentation tables provides an efficient means to conduct:

- What-If Analysis
- Sensitivity Analysis
- Uncertainty Quantification

Risk estimation uncertainty, quality controls, and the use of Monte Carlo simulation are discussed in Sect. 7.3 of Chap. 7, Risk Estimation and Comparison. The focus in this section is the use of What-If analysis to evaluate the change in annualized risk for various risk reduction alternatives. Figure 8.47 presents a computer spreadsheet version of the event tree in Fig. 8.46. (This spreadsheet took approximately 60 min to set up in Excel.)

Fig. 8.47: Computer Spreadsheet Version of Event Tree in Fig. 8.46 for the Existing Annualized Risk

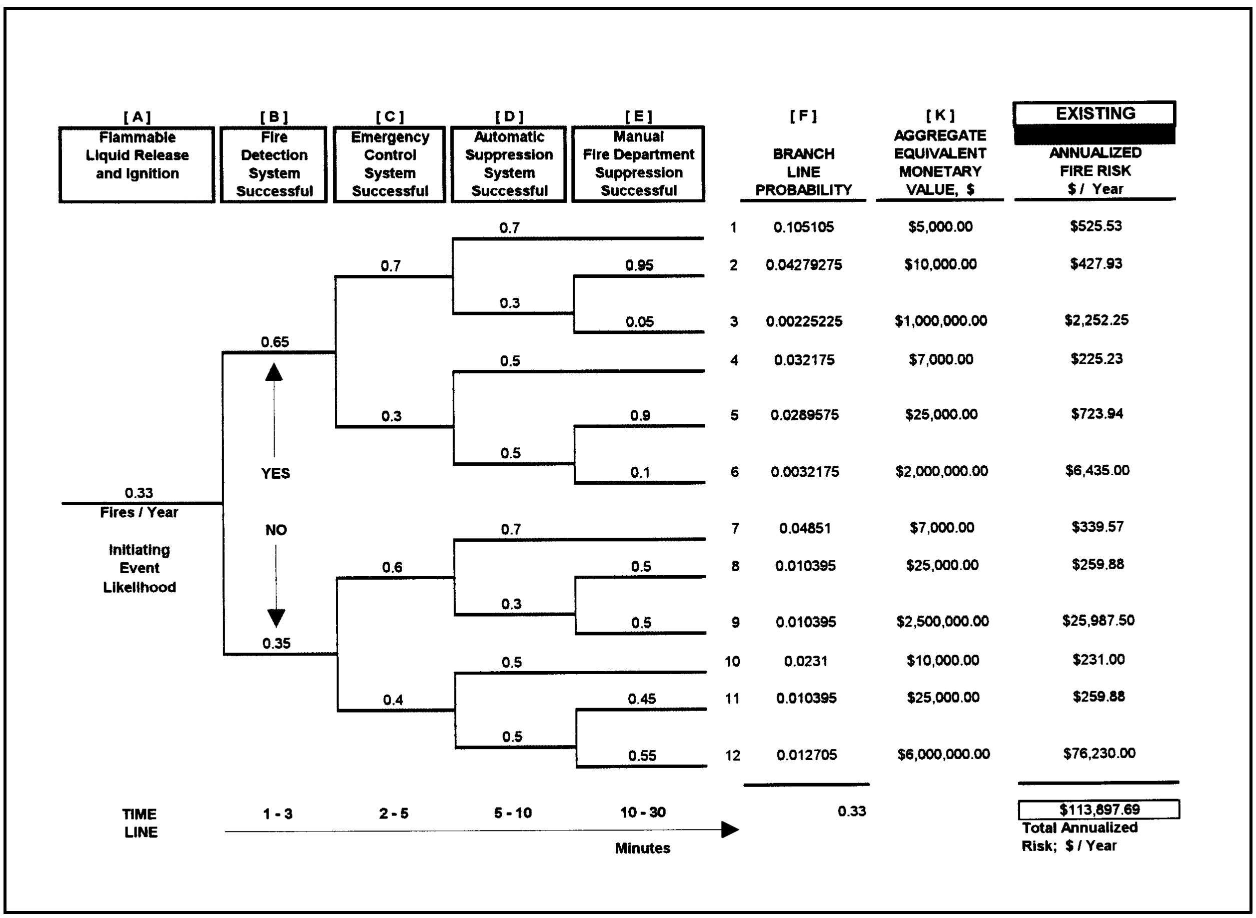


Table 8.26 provides an example of a summary of technically feasible risk reduction alternatives as determined by the risk assessment team. The existing likelihoods or probabilities are from the event tree in Fig. 8.47.

The modified likelihoods or probabilities would be derived from the quantification techniques discussed in Chap. 4, Initiating Event Likelihood, and Chap. 6, Fire Protection Systems Performance Success Probability; which are also summarized in the preceding sections of this chapter. As noted in Table 8.26, documentation references and remarks should be listed in the last column.

Table 8.26: Example Summary of Technically Feasible Risk Reduction Alternatives

EVENT	EXISTING (L) LIKELIHOOD (P) PROBABILITY	TECHNICALLY FEASIBLE RISK REDUCTION ALTERNATIVES	MODIFIED (L) LIKELIHOOD (P) PROBABILITY	REFERENCE & REMARKS
[A] Initiating event likelihood modification	(L) 0.33 events/year	• Improve reliability of pressure/flow instrumentation and alarms to control room • Upgrade pump seal design • Improve inspection/ maintenance to detect incipient leaks	(L) 0.10-0.167 events/year	Reference event likelihood fault tree analysis FTA No. 01A NOTE: Based on Monte Carlo analysis a range of 0.10 to 0.167 was established
[B] Detection system success improvement	(P) 0.65	• Increase availability of existing detection system. Replace old UV detectors with new UV/IR detectors to reduce false trips and downtime	(P) 0.85	Reference fire protection success tree analysis STA No. 02B
[C] Emergency control system (ECS) success improvement	(P) 0.70	• Install a new fail-safe emergency shutoff valve with automatic, fuse link, and remote operation	(P) 0.90	Reference fire protection success tree analysis STA No. 03C Performance criteria would be 0.90 minimum success probability
[D] Automatic sprinkler system upgrade	(P) = 0.70 (1) (P) = 0.50 (2)	• Upgrade existing automatic sprinkler system to a foam-water deluge system	(P) 0.90 (1) (P) 0.80 (2)	Reference fire protection success tree analysis STA No. 04D (1) If ECS is successful (2) If ESC is not successful
[E] Manual fire fighting success improvement	(P) = 0.50 (3) (P) = 0.45 (4)	• To aid in containment and to limit fire spread potential, install a 2-hour rated enclosure around the flammable liquid equipment	(P) 0.95	Reference fire protection success tree analysis STA No. 05E (3) (4) If detection and ECS are not successful

For example purposes, Table 8.27 provides a listing of 15 alternative strategies for modifying the existing risk level of $113,898.00 calculated in the event trees in Figs. 8.46 and 8.47.

The risk reduction alternatives identified in Table 8.27 were evaluated using the Excel computer spreadsheet model. Various alternatives were input into the spreadsheet for evaluation. The numbers in columns [A] → [E] in Table 8.27 are the modified likelihoods or probabilities that are developed using the methods discussed in the previous sections. The last column in Table 8.27 is the ***modified*** total annualized risk calculated for the various alternative strategies.

As presented in Table 8.27, there are ten alternative strategies that may provide a modified total annualized risk level below the risk tolerance limit of $20,000.00. For example purposes, we'll assume that, based on review and team consensus, alternative strategies (4), (11), and (15) were selected for further analysis.

Alternative 4:

4.1 Reduce Initiating Event Likelihood
- Improve flammable liquid pump seal design and instrumentation/alarm monitoring system
- Improve inspection/maintenance frequency

4.2 Upgrade existing fire detection system

4.3 Install new fail-safe emergency shutoff valve

Alternative 11:

11.1 Same as 4.1

11.2 Same as 4.3

11.3 Install a new automatic foam deluge water spray system

Alternative 15:

15.1 Same as 4.1

15.2 Same as 4.3

15.3 Construct a 2-hour fire rated enclosure around flammable liquid equipment

Table 8.27: Example of Modified Risk Estimate for Various Alternative Strategies

ALTERNATIVES	[A] INITIATING EVENT LIKELIHOOD	[B] FIRE DETECTION SYSTEM SUCCESS	[C] EMERGENCY CONTROL SYSTEM (ECS) SUCCESS	[D] AUTOMATIC SUPPRESSION SUCCESS	[E] MANUAL SUPPRESSION SUCCESS	MODIFIED TOTAL ANNUALIZED RISK
1	0.167	—	—	—	—	$ 57,639.13
2	—	0.85	0.90	—	—	$ 33,920.25
3	0.167	0.85	—	—	—	$ 29,413.79
4	0.167	0.85	0.90	—	—	$ 17,165.70
5	0.10	0.85	—	—	—	$ 17,613.05
6	0.10	0.85	0.90	—	—	$ 10,278.86
7	—	—	—	0.90 (1) 0.80 (2)	—	$ 44,944.27
8	0.167	—	—	0.90 0.80	—	$ 22,744.52
9	0.10	—	—	0.90 0.80	—	$ 13,619.48
10	0.167	0.85	—	0.90 0.80	—	$ 11,880.00
11	0.167	—	0.90	0.90 0.80	—	$ 12,455.15
					[E] FIRE RATED ENCLOSURE SUCCESSFUL (3)	
12	—	—	—	—	0.95	$ 18,554.29
13	0.167	—	—	—	0.95	$ 9,389.60
14	0.10	—	—	—	0.95	$ 5,622.51
15	0.167	—	0.90	—	0.95	$ 6,376.08

NOTE: (1) Performance if ECS is successful.
(2) Performance if ECS is NOT successful.
(3) The option of constructing a fire-rated enclosure around the flammable liquid operation was investigated.

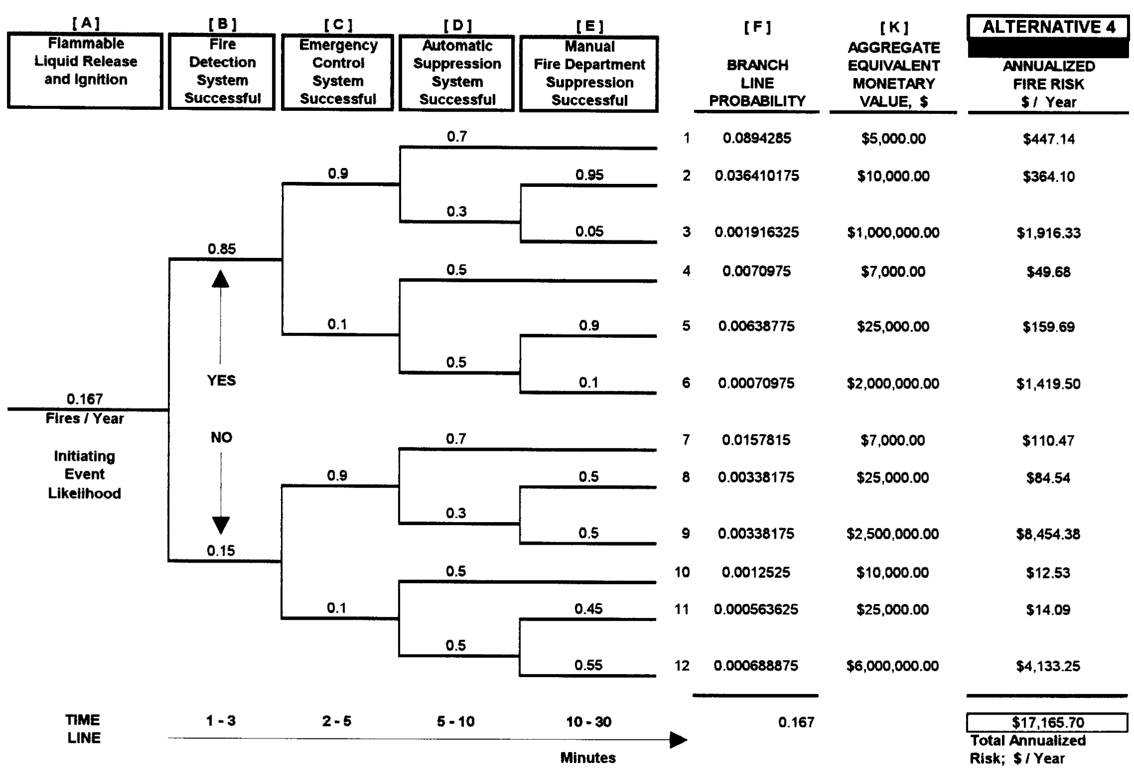
Alternative 4

Alternative 4 resulted in the following modified likelihood (L), success probabilities (P), and total annualized risk:

Alternative I.D.	[A] Initiating Event Likelihood	[B] Fire Detection System Success	[C] Emergency Control System Success	MODIFIED Total Annualized Risk ($/Year)
4	(L) 0.167	(P) 0.85	(P) 0.90	$17,165.70

Figure 8.48 presents the associated Alternative 4 strategy event tree in the Excel spreadsheet format.

Fig. 8.48: Example—Alternative 4 Strategy



Alternative 11

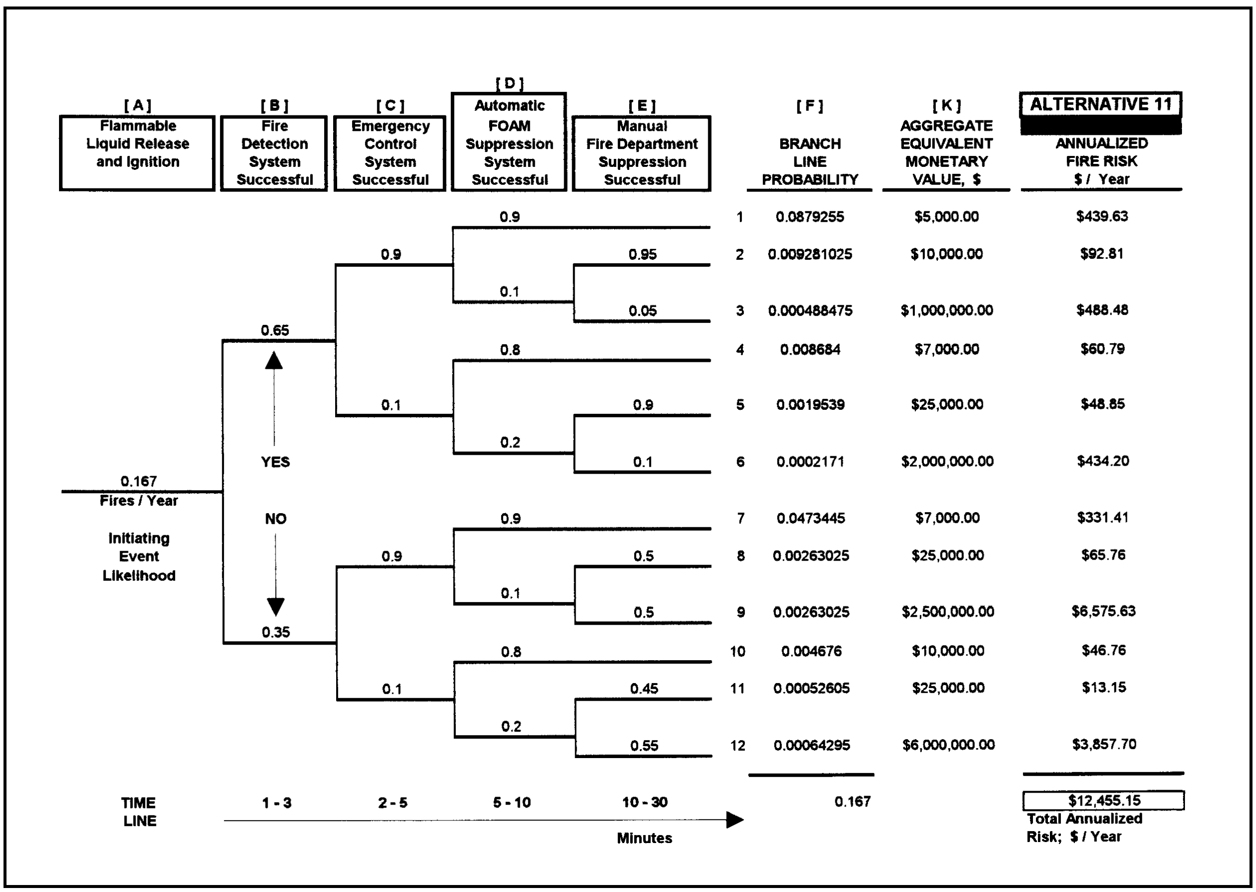
Alternative 11 resulted in the following modified likelihood (L), success probabilities (P) and total annualized risk:

Alternative I.D.	[A] Initiating Event Likelihood	[B] Emergency Control System Success	[C] Automatic FOAM Suppression System Success	MODIFIED Total Annualized Risk ($/Year)
11	(L) 0.167	(P) 0.90	(P) 0.90 (P) 0.80*	$12,455.15

* Estimated probability if emergency control system is not successful.

Figure 8.49 presents the associated Alternative 11 strategy event tree in the Excel spreadsheet format.

Fig. 8.49: Example—Alternative 11 Strategy



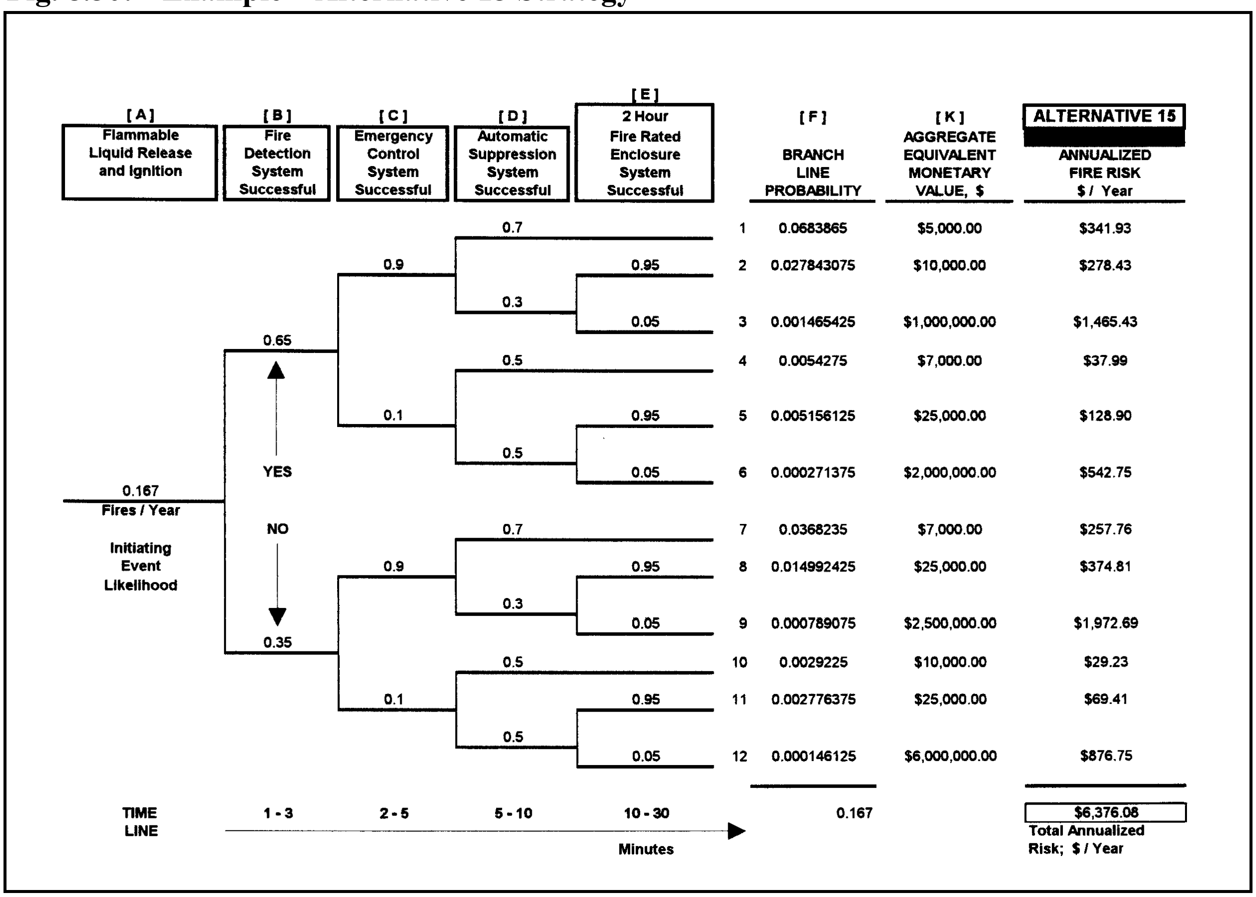
Alternative 15

Alternative 15 resulted in the following modified likelihood (L) success probabilities (P) and total annualized risk:

Alternative I.D.	[A] Initiating Event Likelihood	[B] Emergency Control System Successes	[C] 2-Hour Fire-Rated Enclosure Success	MODIFIED Total Annualized Risk ($/Year)
15	(L) 0.167	(P) 0.90	(P) 0.95	$ 6,376.08

Figure 8.50 presents the associated Alternative 15 strategy event tree in the Excel spreadsheet format.

Fig. 8.50: Example—Alternative 15 Strategy



Uncertainty

In Table 8.27, column [A], you will notice that two reduced initiating event likelihoods were evaluated, 0.167 events/year and 0.10 events/year.

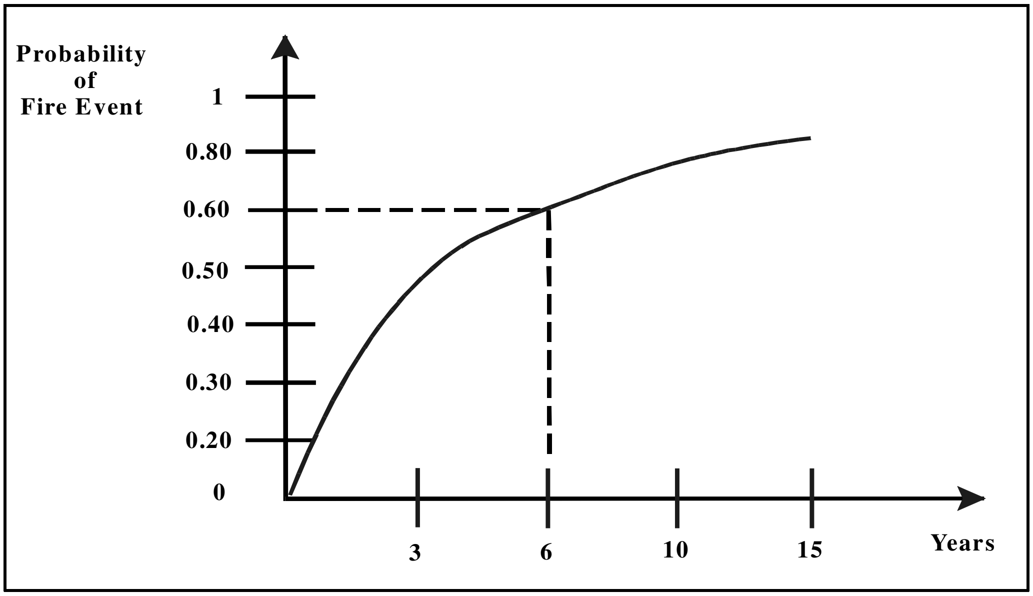
LIKELIHOOD	BASIS
0.33 — 1 fire event / 3 years	Existing likelihood
0.167 — 1 fire event / 6 years	Based on upgrading instrumentation, alarm monitoring, and pump seal design. These upgrades were evaluated using FTA
0.10 — 1 fire event / 10 years	This included the above upgrades and in addition an improved inspection/ maintenance program to detect incipient leak potentials. These factors were added into the FTA

The risk assessment team performed Monte Carlo simulation using a probability distribution to simulate ranges for both hardware equipment failure and human error during inspection and maintenance. Figure 8.51 was developed based on this evaluation. Figure 8.51 indicates that there is:

- A greater than 98% probability that a fire event will occur within a 15-year period,
- An 80% probability that a fire event will occur within 10 years, and
- A 60% probability that a fire event will occur within 6 years.

The risk assessment team decided that an improved inspection/maintenance program was warranted and would be included in the cost evaluation of Alternatives 4, 11, 15. However, to minimize uncertainty, the likelihood of 0.167 (1 fire event potential / 6 years) was still applied in the cost/benefit analysis.

Fig. 8.51: Example – Accumulative Probability of Having an Initiating-Fire Event



8.5.2 Cost Analysis for Selected Risk Reduction Strategies

Costs associated with risk reduction alternatives can generally be broken down into:

- Initial costs (costs incurred during first year)
- Annual costs (ongoing operating costs)

Table 8.28 provides a general overview of some of the primary cost considerations associated with risk reduction alternatives.

Table 8.28: Cost Considerations Associated With Risk Reduction Alternatives

COSTS		REMARKS
Initial Costs, I_c		
Design	I_c	Conceptual design and detailed specifications
Equipment	I_c	Individual components or turn-key system costs
Installation	I_c	Consider plant or process shutdown time to install equipment
Permit/license	I_c	In some cases besides a building code permit, an environmental permit may be required
Pre-startup acceptance testing	I_c	Very important consideration to prove reliability prior to operation
Procedures/training	I_c	Procedures and training functions may have to be conducted prior to equipment/system operation
Annual Costs, A_c		
Operating	A_c	Utilities usage (electrical, air)
Inspection and testing	A_c	In-house or contracted
Maintenance	A_c	In-house or contracted
Replacement	A_c	Useful life of components system, extinguishing agent

Table 8.29 provides an example cost estimate summary for risk reduction strategy 4. The table is broken down into initial and annual costs.

Table 8.29: Example Cost Estimate Summary Sheet for Risk Reduction Strategy 4

	INITIAL COSTS			
RISK REDUCTION STRATEGY 4	DESIGN, EQUIPMENT, INSTALLATION	PERMITS, PRE-STARTUP TESTING, MISC.	TOTAL	INSTALLATION TIME ESTIMATE (MAN-HOURS) REFERENCE/REMARKS
4.1 [A] Improve flammable liquid pump seal design and instrumentation / alarm monitoring system Improve inspection / maintenance program	$ 60,000.00	$ 20,000.00	$ 80,000.00	
4.2 [B] Upgrade existing fire detection system	$ 120,000.00	$ 35,000.00	$ 155,000.00	
4.3 [C] Install new fail-safe emergency shutoff valve	$ 45,000.00	$ 15,000.00	$ 60,000.00	
		TOTAL	$ 295,000.00	

	ANNUAL COSTS			
RISK REDUCTION STRATEGY 4	OPERATING, INSPECTION, TESTING	MAINTENANCE, REPLACEMENT, MISC.	TOTAL	USEFUL LIFE (YEARS) REFERENCE / REMARKS
4.1 [A]	$ 2,000.00	$ 2,000.00	$ 4,000.00	
4.2 [B]	$ 5,000.00	$ 1,500.00	$ 6,500.00	
4.3 [C]	$ 2,000.00	$ 1,500.00	$ 3,500.00	
		TOTAL	$ 14,000.00	

Table 8.30 provides an example cost estimate summary for risk reduction strategy 11.

Table 8.30: Example Cost Estimate Summary Sheet for Risk Reduction Strategy 11

	INITIAL COSTS			
RISK REDUCTION STRATEGY 11	DESIGN, EQUIPMENT, INSTALLATION	PERMITS, PRE-STARTUP TESTING, MISC.	TOTAL	INSTALLATION TIME ESTIMATE (MAN-HOURS) REFERENCE/REMARKS
11.1 [A] Improve flammable liquid pump-seal design and instrumentation/ alarm monitoring system Improve inspection/ maintenance program	$ 60,000.00	$ 20,000.00	$ 80,000.00	
11.2 [C] Install new fail-safe emergency shutoff valve	$ 45,000.00	$ 15,000.00	$ 60,000.00	
11.3 [D] Install a new automatic foam deluge water-spray system	$ 255,000.00	$ 75,000.00	$ 330,000.00	
		TOTAL	$ 470,000.00	

	ANNUAL COSTS			
RISK REDUCTION STRATEGY 11	OPERATING, INSPECTION, TESTING	MAINTENANCE, REPLACEMENT, MISC.	TOTAL	USEFUL LIFE (YEARS) REFERENCE / REMARKS
11.1 [A]	$ 6,000.00	$ 2,000.00	$ 8,000.00	
11.2 [C]	$ 2,000.00	$ 1,500.00	$ 3,500.00	
11.3 [D]	$ 4,000.00	$ 2,500.00	$ 6,500.00	
		TOTAL	$ 18,000.00	

Table 8.31 provides an example cost estimate summary for risk reduction strategy 15.

Table 8.31: Example Cost Estimate Summary Sheet for Risk Reduction Strategy 15

	INITIAL COSTS			
RISK REDUCTION STRATEGY 15	**DESIGN, EQUIPMENT, INSTALLATION**	**PERMITS, PRE-STARTUP TESTING, MISC.**	**TOTAL**	**INSTALLATION TIME ESTIMATE (MAN-HOURS) REFERENCE/REMARKS**
15.1 [A] Improve flammable liquid pump seal design and instrumentation/ alarm monitoring system Improve inspection/ maintenance program	$ 60,000.00	$ 20,000.00	$ 80,000.00	
15.2 [C] Install a new fail-safe emergency shutoff valve	$ 45,000.00	$ 15,000.00	$ 60,000.00	
15.3 [E] Construct a 2-hour fire rated enclosure around flammable liquid equipment	$ 680,000.00	$ 95,000.00	$ 775,000.00	
		TOTAL	$ 915,000.00	

	ANNUAL COSTS			
RISK REDUCTION STRATEGY 15	**OPERATING, INSPECTION, TESTING**	**MAINTENANCE, REPLACEMENT, MISC.**	**TOTAL**	**USEFUL LIFE (YEARS) REFERENCE / REMARKS**
15.1 [A]	$ 2,000.00	$ 2,000.00	$ 4,000.00	
15.2 [C]	$ 2,000.00	$ 1,500.00	$ 3,500.00	
15.3 [E]	$ 2,500.00	$ 2,500.00	$ 5,000.00	
		TOTAL	$ 12,500.00	

8.5.3 Risk Reduction Benefit/Cost Ratios

There are various approaches for combining costs and benefits to help in selecting preferred risk reduction alternatives. Traditional approaches to cost/benefit analysis involve maximizing the benefit/cost (B/C) ratio. That is, in evaluating each risk reduction alternative, one would compute the total discounted benefits and divide by the total discounted costs, and then choose the alternative for which this ratio is greatest. In general a B/C ratio greater than 1.0 is a beneficial investment. The B/C ratio approach provides a very good screening and first-order selection tool.

Calculation Approach

The B/C ratio can be calculated as follows:

$$B/C = \frac{A\ (P/A,\ i,\ n)}{Ic}$$

where A = ARB - Ac

ARB = annualized risk benefit
Ac = annualized cost
Ic = initial cost
P/A = present worth factor
i = interest rate
n = time frame, years

"A" can be defined as the end of period "Cost Avoidance" obtained from implementing a risk reduction strategy. It is equal to the estimated equivalent $ risk reduction benefit (ARB) minus the estimated annual costs (Ac). In the above equation, it is assumed that the "A" is a continuous amount occurring uniformity during each period of time over a specified number of periods (years).

"P/A" denotes the present worth of uniform series "A" (net annual $ cost avoidance) and depends on the interest rate (i) and period of time (n), which is usually expressed in years. The interest rate is usually the minimum attractive rate of return that the company uses to evaluate project investments. "N" is generally the estimated "useful life" of the fire protection upgrade.

The major assumption made in the B/C example estimates that follow for Alternative Strategies 4, 11, and 15 is uniform annual costs. Nonuniform costs (i.e., periodic maintenance, component replacement etc.) can also be handled using engineering economic-analysis methods.

Other methods besides B/C analysis can be used. Two of these include rate of return (ROR) and payback period.

Engineering Economics — Some References

- Watts, John M. *SFPE Handbook of Fire Protection Engineering*, Second Edition. Chaps. 5–6, Engineering Economics, 1995.[4]
- Steiner, Henry Malcolm, *Engineering Economic Principles*, McGraw-Hill, Inc., N.Y. 1992.[5]

Using the B/C approach, the ratios for risk reduction strategies 4, 11, 15, are calculated for example purposes.

Benefit/Cost Ratio – Risk Reduction Strategy 4

ARB = \$113,897.64 (existing risk) – \$17,165.70 (modified risk)
= \$96,731.99
Ic = \$295,000.00 (initial cost)
Ac = \$14,000.00 (annual cost)
i = 12% (assumed)
n = 20 years

$$B/C = \frac{A\,(P/A, i, n)}{Ic}$$

$$A = ARB - Ac$$

$$B/C = \frac{(\$96{,}731.99 - \$14{,}000.00)\,(P/A, i, n)}{\$295{,}000.00}$$

Note: The (P/A, i, n) present-worth factor can be found in any Engineering Economics Book or by using a business calculator. For this example, the factor is 7.469.

$$B/C = \frac{(\$82{,}731.99)\,(7.469)}{\$295{,}000.00}$$

$$B/C = 2.09$$

Benefit/Cost Ratio – Risk Reduction Strategy 11

ARB = $113,897,64 (existing risk) – $ 12,455.15
= $101,424.54
Ic = 470,000.00
Ac = $18,000.00
i = 12% (assumed)
n = 20 years

$$B/C = \frac{A\ (P/A,\ i,\ n)}{Ic}$$

A = ARB – Ac

$$B/C = \frac{(\$101{,}424.54 - \$18{,}000.00)\ (7.469)}{\$470{,}000.00}$$

B/C = 1.33

Benefit/Cost Ratio – Risk Reduction Strategy 15

ARB = $113,897,64 (existing risk) – $6,376.08 (modified risk)
= $107,521.36
Ic = $915,000.00
Ac = $12,500.00
i = 12% (assumed)
n = 20 years

$$B/C = \frac{A\ (P/A,\ i,\ n)}{Ic}$$

A = ARB – Ac

$$B/C = \frac{(\$107{,}521.26 - \$12{,}500.00)\ (7.469)}{\$915{,}000.00}$$

B/C = 0.77

Table 8.32 summarizes the calculated B/C ratios for the selected risk reduction strategies.

Table 8.32: Summary of B/C Ratios For Selected Risk Reduction Strategies

RISK REDUCTION STRATEGY	B/C RATIO	REMARKS
4	2.09	Includes a major upgrade of the existing detection/alarm system
11	1.33	Includes the installation of a new automatic foam suppression system
15	0.77	Involves the installation of a 2-hour fire rated enclosure around the flammable liquid equipment
Note: a B/C ratio greater than 1.0 is a beneficial investment.		

From a first look at Table 8.32, it appears that risk reduction strategy 4 would be preferred because it has the highest risk reduction B/C ratio. However, there are usually two more steps needed before a decision can be made:

- Recognition of other decision variables
- Integration of the decision maker's preferences

8.6 DECISION MAKING

In Sect. 8.5, an example was presented for developing benefit/cost (B/C) ratios for three alternative risk reduction strategies. The results of the B/C analysis are reproduced in Table 8.33.

Table 8.33: Summary of B/C Ratios

RISK REDUCTION STRATEGY	B/C RATIO	IS STRATEGY OR ALTERNATIVE ECONOMICALLY JUSTIFIED?
4	2.09	Yes
11	1.33	Yes
15	0.77	No

The information provided from B/C analysis of alternative strategies includes:

- The estimated dollar value of the annualized risk reduction
- The initial and annual cost
- If the calculated B/C Ratio exceeds 1.0, the strategy is economically beneficial.

In some cases, there will be more than one alternative strategy where the B/C ratio is greater than 1.0. This is the case in Table 8.33 where both Alternative Strategies 4 and 11 exceed 1.0. When this occurs, the next step usually fits into one of the following three approaches:

1. Select the alternative strategy with the highest B/C ratio.
2. If the B/C ratios are close, conduct additional detailed engineering economic analysis.
3. Evaluate the decision maker's preferences.

This section addresses the third approach, defining and quantifying the decision maker's preferences.

Decision Maker's Preferences

The risk reduction strategy selection team generally includes members of the team that conducted the risk-based study along with additional management decision makers from Risk Management, Engineering, and Operations.

Let's assume that the following decision making factors are developed by the team:

A. Cost-effectiveness (defined by B/C ratios)
B. Ease of installation/maintenance
C. Independent of manual fire extinguishment (i.e., minimal reliance on manual intervention)

The cost-effectiveness benchmark for a risk reduction strategy is usually that the B/C ratio is greater than 1. Ease of installation/maintenance may deal with the extent of production downtime (i.e., having to take production equipment, process operation off-line for installation and maintenance). Independent of manual fire extinguishment involves concern with alternative strategies that even after implementation, still require major dependance on fire brigades or public fire departments. For plants that are downsizing, fire brigade resources or uncertain public fire department response can be a major issue.

These three preference factors for decision makers were assumed so that an example could be developed in this section on how to incorporate multiple decision variables into the selection process.

There are many other decision variables that may be important to the decision making team. Some decision issues might include worker exposure (e.g., having maintenance workers in an enclosed area protected by carbon dioxide) or environmental impacts (e.g., having contaminated water spray or foam runoff into soil or water ways creating an environmental issue). In some cases, companies may lean toward installing the latest protection technology, while other companies want to rely on protection methods they are experienced with.

Decision Analysis Tools

There are various decision analysis (DA) methods and computer programs available for incorporating multiple variables into the decision making process. Explanation of each method is beyond the scope of this section. The reference listed in the following box provides a very good description of DA tools with many examples and supplementary references.

References on Decision Analysis

"Tools For Making Acute Risk Decisions," published by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers, N.Y., N.Y., 1995[6].

Analytic Hierarchy Process

The Analytic Hierarch/process (AHP) is a very popular approach used by decision making teams. This is basically a weighted-scoring approach that provides consistency in terms of incorporating multiple variables into the decision analysis process and can produce a relative prioritization of risk reduction strategies. Detailed descriptions and a discussion of the pros and cons of this method are provided in reference [6]. The following presents a simplified example of applying AHP.

The following example evaluates a decision making team's preferences for selecting a risk reduction strategy based on:

- Cost-effectiveness
- Ease of installation/maintenance
- Minimum reliance on manual fire extinguishment

Alternative risk reduction strategies 4 and 11 were evaluated.

Note: These alternatives were described in the previous section. Alternative 15 was screened out because the B/C ratio was less than 1.

"Pairwise" Comparison

Table 8.34 presents an example of the pairwise comparison for the decision making team's decision factors. The team's first step is to compare the relative importance of the three decision factors. In this example, the decision making team compared the importance of cost-effectiveness to the ease of installation. The team felt that cost-effectiveness was twice as important as ease of installation/maintenance. They also felt that the cost-effectiveness and independence of manual fire extinguishment had equal importance as one of the company's long-term goals involved changing from a structural fire brigade to an emergency response team, which placed more reliance on quick "automatic" extinguishment capabilities.

Note in Table 8.34 that in the first row, second column, a 2 is placed, indicating the cost-effectiveness is twice as important as ease of installation/maintenance. Therefore in row two, column one, a ½ is placed, indicating that the ease of installation and maintenance is half as important as the cost-effectiveness. This approach is used to compare each decision factor to the others and complete the matrix.

Table 8.35 provides normalization of the pairwise comparison. Table 8.36 provides the prioritization, or weighted importance, of the decision factors.

Table 8.34: Example – Pairwise Comparison Matrix for Preference Factors

DECISION FACTORS	[A] COST-EFFECTIVENESS (B/C RATIOS)	[B] EASE OF INSTALLATION / MAINTENANCE	[C] INDEPENDENT OF MANUAL FIRE EXTINGUISHMENT
Cost-effectiveness (B/C ratios)	1	2	1
Ease of installation/maintenance	1/2	1	1/2
Independent of manual fire extinguishment	1	2	1
Column Totals	2.5	5.0	2.5

Table 8.35: Example – Normalized Pairwise Comparison Matrix for Preference Factors

DECISION FACTORS	[A] COST-EFFECTIVENESS (B/C RATIOS)	[B] EASE OF INSTALLATION / MAINTENANCE	[C] INDEPENDENT OF MANUAL FIRE EXTINGUISHMENT
Cost-effectiveness (B/C ratios)	$\frac{1.0}{2.5} = 0.40$	$\frac{2}{5} = 0.40$	$\frac{1.0}{2.5} = 0.40$
Ease of installation/maintenance	$\frac{0.50}{2.5} = 0.20$	$\frac{1.0}{5.0} = 0.20$	$\frac{0.5}{2.5} = 0.20$
Independent of manual fire extinguishment	$\frac{1.0}{2.5} = 0.40$	$\frac{2}{5} = 0.40$	$\frac{1.0}{2.5} = 0.40$
Column totals	1.0	1.0	1.0

Table 8.36: Example – Priority of Preference Factors

DECISION FACTORS	[A] COST-EFFECTIVENESS (B/C RATIOS)	[B] EASE OF INSTALLATION / MAINTENANCE	[C] INDEPENDENT OF MANUAL FIRE EXTINGUISHMENT	PRIORITY (A+B+C) / 3.0
Cost-effectiveness (B/C ratios)	0.40	0.40	0.40	0.40
Ease of installation/ maintenance	0.20	0.20	0.20	0.20
Independent of manual fire extinguishment	0.40	0.40	0.40	0.40

Table 8.37 provides the pairwise comparison of Alternatives 4 and 11 as related to cost-effectiveness. In this example, the decision making team felt that Alternative 4 was twice as cost-effective as Alternative 11 because of its higher B/C ratio. Table 8.38 illustrates normalization and prioritization of the results.

Table 8.39 provides the pairwise comparison of Alternatives 4 and 11 as related to ease of installation (the decision making team felt that Alternative 4 would be three times easier to install and maintain than Alternative 11, which consists of a complex foam-water system design. Table 8.40 normalizes and prioritizes the results.

Table 8.41 provides the pairwise comparison of Alternatives 4 and 11 as related to independence of manual fire extinguishment. The decision making team felt that Alternative 11 was five times more independent than Alternative 4, due to the quick automatic extinguishing capabilities of the foam system. Table 8.42 normalizes and prioritizes the results.

Table 8.43 presents the calculation of the overall priorities based on this example evaluation.

Table 8.37: Cost-Effectiveness — Pairwise Comparison of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11
Alternative 4	1	2
Alternative 11	1/2	1
Column Total	1.5	3.0

Table 8.38: Cost-Effectiveness — Normalization and Priority of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11	PRIORITY
Alternative 4	$\frac{1}{1.5} = 0.67$	$\frac{2}{3.0} = 0.67$	(0.67 + 0.67)/2 = 0.67
Alternative 11	$\frac{0.5}{1.5} = 0.33$	$\frac{1.0}{3.0} = 0.33$	(0.33 + 0.33)/2 = 0.33
Column Total	1.0	1.0	1.0

Table 8.39: Ease of Installation/Maintenance — Pairwise Comparison of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11
Alternative 4	1	3
Alternative 11	1/3	1
Column Total	1.33	4.0

Table 8.40: Ease of Installation/Maintenance — Normalization and Priority of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11	PRIORITY
Alternative 4	$\frac{1}{1.33} = 0.75$	$\frac{3}{4} = 0.75$	(0.75 + 0.75)/2 = 0.75
Alternative 11	$\frac{0.33}{1.33} = 0.25$	$\frac{1}{4} = 0.25$	(0.25 + 0.25)/2 = 0.33
Column Total	1.0	1.0	1.0

Table 8.41: Independent of Manual Fire Extinguishment — Pairwise Comparison of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11
Alternative 4	1	1/5
Alternative 11	5	1
Column Total	6	1.2

Table 8.42: Independent of Manual Fire Extinguishment — Normalization and Priority of Alternatives

ALTERNATIVE RISK REDUCTION STRATEGIES	ALTERNATIVE 4	ALTERNATIVE 11	PRIORITY
Alternative 4	$\frac{1}{6} = 0.17$	$\frac{0.20}{1.2} = 0.17$	(0.17 + 0.17)/2 = 0.17
Alternative 11	$\frac{5}{6} = 0.83$	$\frac{1}{1.2} = 0.83$	(0.83 + 0.83)/2 = 0.83
Column Total	1.0	1.0	1.0

Table 8.43: Calculation of Overall Priorities

ALTERNATIVE RISK REDUCTION STRATEGIES	COST-EFFECTIVENESS (0.40)	EASE OF INSTALLATION / MAINTENANCE (0.20)	INDEPENDENT OF MANUAL FIRE EXTINGUISHMENT (0.40)	OVERALL PRIORITY OF ALTERNATIVES
Alternative 4	0.67 x 0.40 +	0.75 x 0.20 +	0.17 x 0.40	= 0.49
Alternative 11	0.33 x 0.40 +	0.25 x 0.20 +	0.83 x 0.40	= 0.51

Based on Table 8.43, Alternative 11, which includes installation of a foam system, has a slightly higher rating than Alternative 4. By using an AHP computer program, additional decision variables could be easily added, and sensitivity analysis could be performed to determine how individual pairwise comparisons affect the overall priorities. Using an AHP computer program, a decision making team could perform an evaluation similar to the preceding example in one or two meetings.

8.7 RISK MONITORING

Following the selection and implementation of the best risk reduction strategy, risk monitoring controls become the next consideration. In this section monitoring will be broken down into:

- Installation and start-up risk control
- Operational risk monitoring
- Fire protection system impairments
- Performance feedback

8.7.1 Installation and Start-Up Risk Control

The risk associated with the implementation or installation of a risk reduction strategy is often overlooked. For example, installation of a foam-water fire protection system for Process C may require cut-in and connection to the plant's underground fire main system. The cut-in causes the FPSs for Process A and B to come off-line and therefore increases the overall risk level for Process Area ABC. Another example could be the installation of a nitrogen-gas-inerting system into a vessel in Process A to reduce the F&E risk. During the hot-tapping of the gas piping to the vessel, the overall fire exposure in Process Area ABC is increased. Many more types of examples could be added here, but the point is, it is very important to identify and evaluate these types of installation risks.

Reduction of implementation or installation risk requires planning, timing, and precautions. Work needs to be planned and scheduled to minimize fire-exposure potentials, minimize FPS impairments, and maximize worker safety.

Once the installation is complete, the next step is to perform a pre-startup safety and operational review and acceptance testing of FPSs. It is common practice in the process industry to use pre-startup checklists and sign-off sheets. The risk assessment team should be part of the review and sign-off.

If the plant must comply with OSHA Process Safety Management regulations,[7] then employers are required to perform a pre-startup safety review for new facilities and for modified facilities when there may be changes in process safety information. The pre-startup safety review must confirm that:

- Construction is in accordance with design specifications.
- Safety, operating, maintenance, and emergency procedures are in place and adequate.
- Mitigation actions necessary for start-up are in place (including FPSs).
- Operating procedures are in place and employees are trained.

Acceptance testing of FPSs cannot be overemphasized. Detailed inspection and proof-testing needs to be conducted.

8.7.2 Operational Risk Monitoring

The three primary risk monitoring controls during the operational phase are:

- Management of change programs
- Equipment inspection, maintenance, testing (IMT) programs
- Fire safety self inspection

Modifications to occupancy, equipment, operations, and FPSs over the life cycle need to be documented in a Management of Change (MOC) program as changes may have an impact on the fire-risk level. A written procedure should be in place to initiate, document, and review the change.

In general, the MOC program should include several modifications, among them those made:

- to facilities, occupancies, or operations;
- to production equipment and instrumentation;
- to FPSs;
- to inspection, maintenance, and testing procedures;
- based on new or amended design standards and practices;
- to fix control-system software errors;
- to correct systematic failures identified during testing;
- as a result of a failure rate higher than desired; and
- as a result of staffing change that may affect operations or emergency response.

The MOC team should be organized to review and screen change requests. Usually there are three levels of evaluation:

- Qualitative review
- Hazard analysis
- Risk assessment

For simple changes, a qualitative review and sign-off may be all that is needed. For changes that may increase the hazard or risk, more detailed quantitative analysis may be warranted.

For plants that must comply with OSHA Process Safety Management Regulations.[7] employers are required to establish and implement written procedures to manage any changes to facilities or to process chemicals, technologies, or equipment. Procedures must address the following:

- Technical basis for the change
- Impact on safety and health
- Modifications to operating procedures
- Necessary time period for the change
- Authorization requirements for the change

In addition, employees must be trained prior to implementation. Process safety analysis information and operating procedures must be revised.

Equipment Inspection, Maintenance, Testing (IMT) Programs

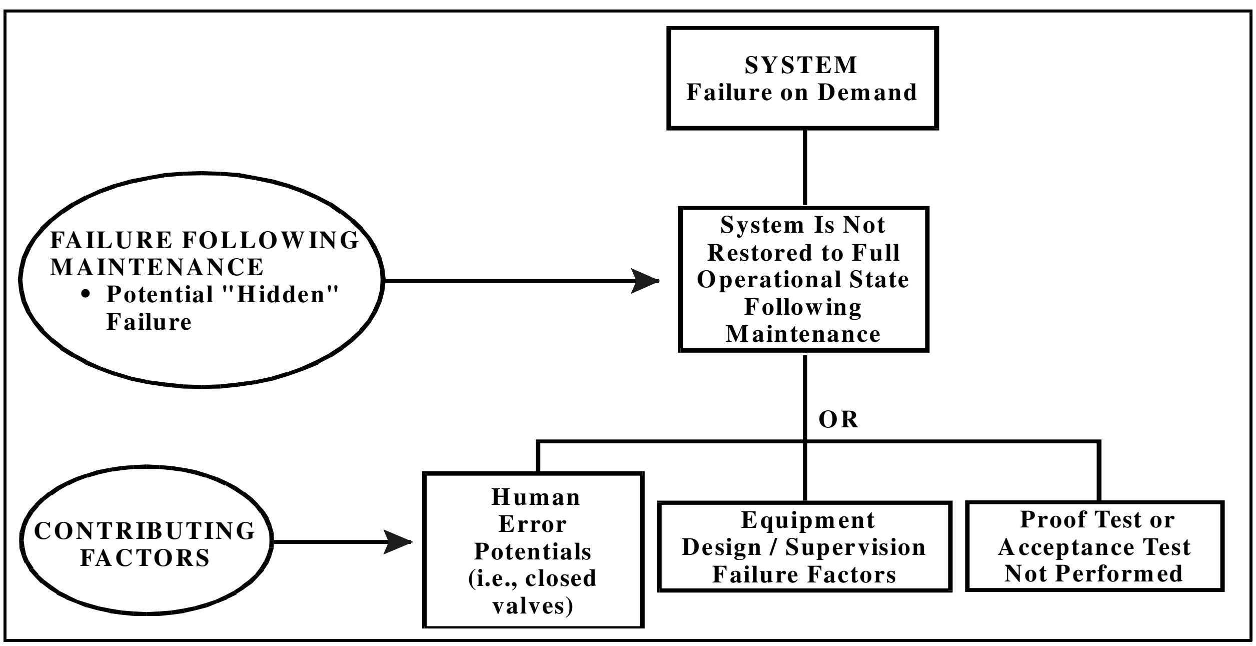
The quality of the IMT program will have a major impact on equipment and system failure rates. Good inspection programs can help identify incipient failure potentials and help prevent major failures. It is important to remember that many failures occur following maintenance operations. For example, the following general information has been reported on maintenance-induced failures:

- Air Force
  - 40% of failures are induced by previous maintenance (complex weapon systems)
- North American Electric Reliability Council
  - Approximately 50% of forced outages occur within three months of a planned maintenance outage or overhaul
- Chemical, petrochemical industry
  - Approximately 25–35% of process equipment failures involves human-maintenance errors.

It is important to recognize the potential for maintenance-induced errors for FPSs. Figure 8.52 provides a general illustration of contributing factors, indicating that when possible, proof-testing to verify system restoration and operation should be conducted following maintenance functions.

As equipment becomes more complex and automated via computer controls, maintenance programs regarding training and certification become even more important.

Fig. 8.52: Potential for Failure Following Maintenance



Fire Safety Self-Inspection

Engineered FPSs are a vital factor in the reduction of large fire losses at industrial facilities. Statistical studies of suppression by properly designed and maintained fire protection equipment have proven these systems effective. Unfortunately, reports of large fire losses stemming from malfunctioning fire protection equipment continue. Some of the recurring problems include the following:

- Undetected closure of sprinkler-system control valves
- Inoperative fire pumps
- Low levels in water-supply tanks
- Malfunctioning special suppression equipment
- Inoperative fire doors
- Inoperative fire-detection systems

Management must take a positive approach in establishing programs for periodic IMT of fire protection equipment. Equally important is management's need for a documented self-inspection program as part of ongoing firesafe plant operation.

Once an adequate program has been established and implemented, inspections must be conducted by individuals knowledgeable in the purpose, operation, and testing of the equipment.

To simplify facility self-inspections, forms appropriate for the occupancy and equipment should be used. Forms should be specific enough to be usable and comprehensive enough so that no element of prevention or protection is overlooked.

As part of a thorough inspection, regardless of frequency, the occupancy should be inspected for the following:

- Poor housekeeping, waste, and accumulation of combustible materials
- Careless smoking
- Improperly stored flammable/combustible liquids
- Blocked electrical switch gear and storage of combustible material in electrical rooms
- Improper maintenance of electrical conduits and junction boxes
- Abnormal amounts of combustible in-process or finished products in areas where FPS have not been adequately designed for this overload

Upon completion of inspections and testing, reports should be forwarded to the facility manager. For those deficiencies that are severe and could be of imminent danger, the facility manager should be notified immediately and should take immediate action.

8.7.3 FPS Impairments

Many large fire losses have been directly attributed to impaired FPSs or equipment. Major property insurance companies, during routine facility inspections, continue to find all types of FPSs out of service. The need for an effective impairment notification program is evident to eliminate the possibility of undetected FPS shutdowns.

A protection system may become impaired for a number of reasons (e.g., maintenance, renovation, construction, equipment failure, or failure to reactivate the system or device).

Facility managers and loss control managers should be notified immediately of any impairments during normal working hours. During off hours, depending on the seriousness of the impairment, these same individuals may still want to be notified. This procedure should be addressed in detail in the company policy.

Any impairment program should require:

1. Assigning responsibility and authority to control the impairment to one individual. This is normally a plant engineer or fire protection safety supervisor. In an emergency, a shift supervisor or fire-brigade chief may have the authority to impair a system, but the overall responsibility for the impairment remains with the loss control manager.
2. Educating plant personnel in basic precautions to be taken when a protection system or equipment is impaired. Precautions include:
   - Limiting the number, scope, and duration of impairment
   - Providing back-up fire protection measures
   - Avoiding cutting and welding operations
   - Shutting down any hazardous processes
   - Completing impairment work in a timely manner
   - Restoring protection system upon completion of all work
   - Verifying, by testing, that the protection system is operational

Assess Fire System Impairment Effects with Event Tree Analysis

FPSs impairments that affect fire risk can be assessed using the event tree risk model developed for the area under evaluation. Using event tree "What-If" analysis is especially useful for evaluating impairments to FPS and justifying back-up precautions.

For example, assume the event tree in Fig. 8.53 represents the existing risk level for Process Area ABC. The existing annualized risk is estimated at $12,455.15. The Maintenance Manager indicates that the plant's fire pump will be out of service for 30 days for repairs and further indicates that ABC process operations, because of contract agreements, cannot be shut down during this impairment.

With the fire pump out of service, the foam fire-suppression system cannot perform successfully. Figure 8.54 provides estimation of the annualized risk level with the foam system impaired. (Note: the success branch lines for foam suppression system success in the event tree were changed to zero.) The risk level increased to $93,996.16.

Using this assessment, the following can be calculated:

Existing risk:	$ 12,455.15
Risk level with foam system impairment:	$ 93,996.16
Increase in risk from the foam system impairment:	$ 81,541.01
Risk increase allocated to a 30-day impairment:	$ 6,795.00

The potential fire-risk increase over the 30-day impairment period is estimated at $6,795.00. Therefore, from a risk maintenance perspective (i.e., trying to maintain risk near its existing tolerable risk level during an impairment), $6,795.00 could be used to provide temporary fire-protection measures such as renting a portable fire pump or increasing fire surveillance during the impairment.

Fig. 8.53: Example Event Tree Presenting Existing Risk Level

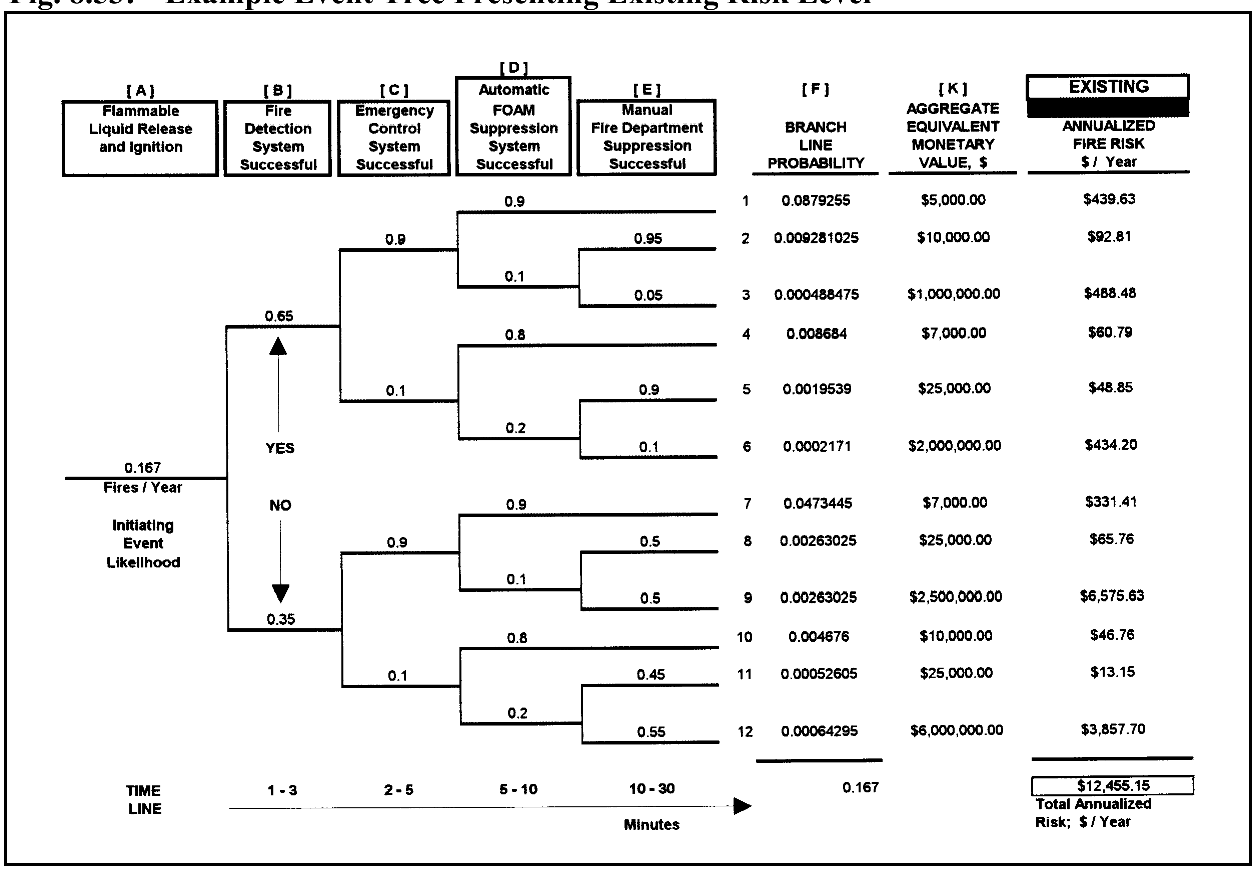
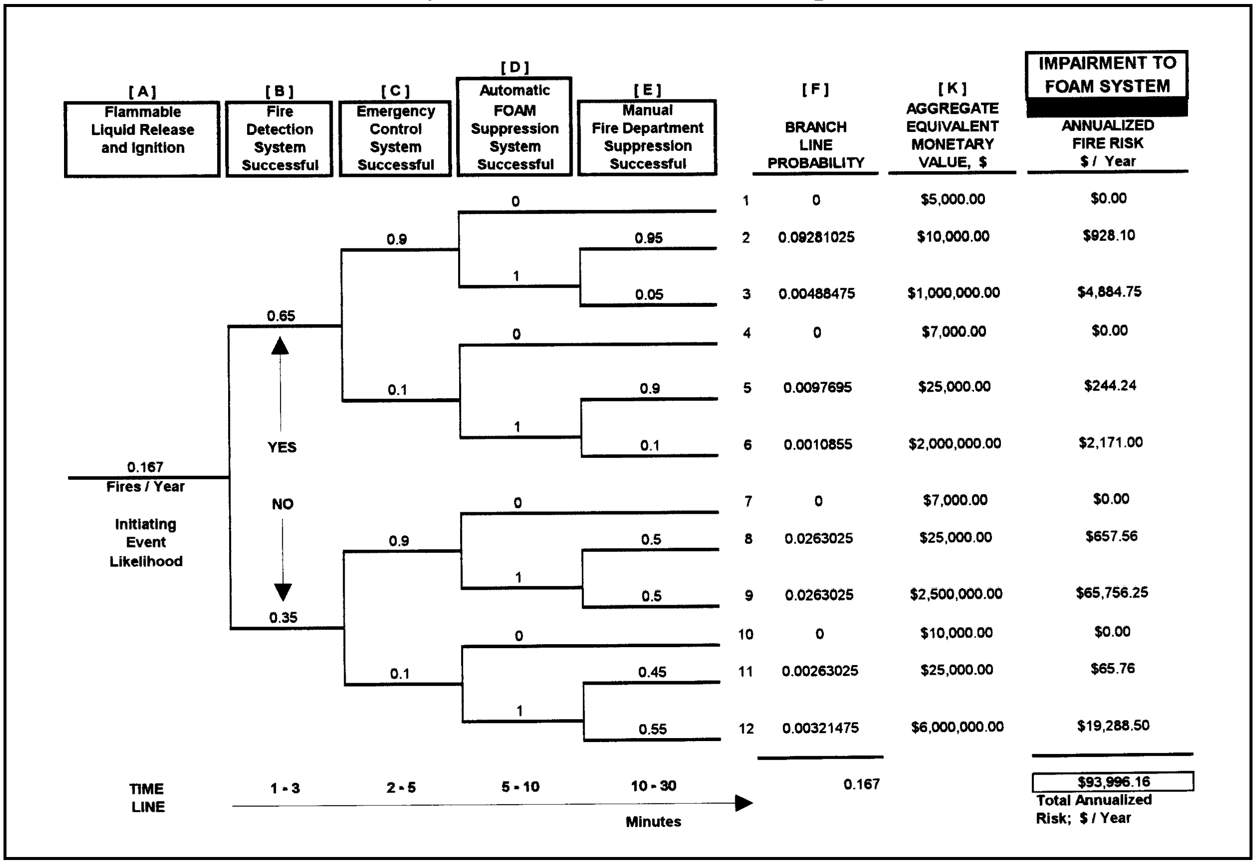


Fig. 8.54: Example Event Tree Presenting Modified Risk Level Due to an Impairment (Automatic Foam System Success is 0 Due to Impairment)



8.7.4 Performance Feedback

The performance feedback being addressed here is the performance of the fire-risk monitoring program. This program provides a set of risk controls to maintain a facility, area, or operation below the established risk tolerance levels.

Management should assign review responsibility and authority to correct problems that may increase the risk level. Review and sign-off should include:

- Fire safety self-inspection reports
- Management of change (MOC) projects
- IMT reports
- FPS impairment results
- Incident investigation reports

If deficiencies are identified and action item recommendations are made, then completion of these actions needs to be assigned to a specific department and individual (single-point accountability) with a firm schedule for completion. Tracking of the status of recommended action items should be an integral point of the performance-feedback report system. Also, management audits should be conducted periodically to verify the performance of risk-monitoring programs.

Incident investigations are an important part of performance tracking and correction. It is important to investigate every incident that results in, or could have reasonably resulted in, a major release, fire, or explosion accident. Some incident-investigation program factors include:

- Prompt investigations of incidents
- Skilled, knowledgeable investigation teams (plant and process knowledge as well as other specialties, such as fire loss investigation skills)
- Complete and detailed incident reports should include:
  - Incident date and date investigation begins
  - Incident description, contributing factors, and resulting recommendations
- Review and retention of reports (review by appropriate personnel within the facility and retention in loss incident files)
- Response and resolution to recommendations

The risk-informed, performance-based assessment methods described in this book, such as initiating-event fault tree analysis, the event tree fire risk model with time lines, and exposure modeling of F&E incidents, provide powerful analytical tools for supplementing accident investigations.

8.8 REFERENCES

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