

Risk - Informed, Performance - Based Industrial Fire Protection



An Alternative to Prescriptive Codes



Thomas F. Barry, P.E.

Risk-Informed, Performance-Based Industrial Fire Protection

First Edition

Copyright © 2002 by TFBarry Publications

All rights reserved. No part of this book may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system without written permission from the author, except for the inclusion of brief quotations in a review.

Published by:

Tennessee Valley Publishing
P. O. Box 52527
Knoxville, Tennessee 37950

Printed in the United States of America

Library of Congress Control Number: 2002112175

ISBN 1-882194-09-8

Although the author and publisher have made every effort to ensure the accuracy and completeness of information contained in this book, we assume no responsibility for errors, inaccuracies, omissions, or any inconsistency herein.

Excel is a registered trademark of Microsoft Corporation. Some of the product names and company names used in this book have been used for identification purposes only and may be trademarks.

ATTENTION CORPORATIONS, UNIVERSITIES, COLLEGES AND PROFESSIONAL ORGANIZATIONS:
Quantity discounts are available on bulk purchases of this book for educational, and gift purposes. For information, visit www.fireriskforum.com, Email: tfbarry@fireriskforum.com.

The book cover was designed by Christopher G. Barry.

Dedicated to

Karin, Christopher, Mackenzie, Irene, and Gerald Barry

With Love

Preface



The concept of performance-based fire protection engineering, although introduced into practice in the United States during the past decade, is not new. The 1965 National Fire Protection Association Meeting in Washington, D.C., included the presentation of the following paper: “Fire Protection and the Performance Concept.” In addition, in 1978 the National Bureau of Standards published a study report entitled: “Toward a Performance Approach to Life Safety From Fire in Building Codes and Regulations.”

In this book, Tom Barry has successfully merged the concepts of fire risk analysis, risk assessment, and probability modeling into the performance code process being introduced in fire protection engineering today. As defined by Barry, Risk-Informed, Performance-Based Fire Protection is an integration of decision analysis and quantitative risk assessment with a defined step approach for quantifying the performance success of fire protection systems.

There is no doubt that the concept of performance-based fire protection engineering requires that today’s fire protection engineer be thoroughly educated in the means to quantify the judgmental decisions of yesterday. As Tom Barry has indicated: “Risk-based analysis and decision making is widely used by many agencies of the U.S. government, the chemical process industry, the telecommunications industry, the aviation industry, and others. The application of fire and explosion risk and performance-based decision analysis will certainly become an alternative to prescriptive codes.” Risk-informed, performance-based fire protection engineering involves applying quantitative risk assessment evaluation techniques in conjunction with traditional fire protection engineering methods to make informed decisions about the effect of fire and explosion risk on the safety of personnel and the continued operation of the business.

This book is a definite necessity for every practicing fire protection professional. The author has examined and explained the sometimes complicated procedures with excellent examples and outstanding graphics, which benefit both the novice and the practitioner.

Dr. John L. Bryan

From the Author



The steps, methods, and tools described in this book are intended to bridge the gap between qualitative and quantitative fire risk assessment by filling the void between educated opinion and objective decision support information.

The book presents a risk-based decision support process to help identify fire safe design and protection alternatives and then select the best alternative(s) based on risk tolerance, meeting the performance intent of applicable codes, and cost/benefit criteria.

Fire safe design responsibility includes many groups; architects, facility and process designers, fire protection and safety engineers, loss control and risk managers; review and approval groups including building code officials, fire marshals, regulatory agencies, and insurance companies. In this book, all these groups are placed under one title, “Risk-Based Decision Makers.”

“Risk-Informed” provides another dimension to the traditional approaches taken towards life safety and fire protection design methods and practices. It provides a path forward for situations where applying prescriptive codes is not feasible or cost-effective, where applying performance-based deterministic modeling has many uncertainties, or where there is a desire to conduct cost/benefit analysis of numerous fire protection alternatives.

I have worked in the industrial fire protection field for 24 years. My Masters degree is in Fire Protection Engineering from Worcester Polytechnic Institute (WPI), Worcester, MA. My professional engineering registration is in Fire Protection. Since 1989, most of my consulting work has been in the chemical, oil, gas, electronics, government, and nuclear sectors and has involved some or all of the steps described in this book. More and more plant managers and risk managers are asking for risk-informed, performance-based information so that they can make more intelligent decisions concerning fire and explosion risk reduction.

All the information in this book is based on real world experience using established risk and reliability analysis techniques specifically applied to fire and explosion risk. The chapter numbering follows the step numbering, which leads the reader from project definition (Chapter 1, Step 1) to the cost/benefit analysis of risk reduction alternatives (Chapter 8, Step 8).

A Fire Risk Forum (FRF) web site has been set up to provide an online continuing education resource. The web site address is www.fireriskforum.com and is described in Chapter 9, Moving Forward.

I hope you enjoy this book and find it useful.

Thomas F. Barry, P.E.
tfbarry@fireriskforum.com

Acknowledgments



I am indebted to a number of individuals who helped make this book a reality.

First I would like to acknowledge the contributions of Ken Dungan, Risk Technologies, LLC. Ken, who is a past president and fellow of the Society of Fire Protection Engineers, is a leader in the fire protection community concerning the advancement of performance-based and risk-based fire protection methods. Ken's advice, chapter reviews, and suggestions were invaluable in the development of this book.

I wanted to develop a book which was part "how-to," part "textbook," and part "application-insight." The risk-informed, performance-based concept needs to be integrated into undergraduate and graduate fire safety and fire protection programs. I am very grateful to Dr. John Bryan, who was appointed Professor Emeritus at the University of Maryland following his retirement from acting Chair, Department Head, and Professor of the school's Fire Protection Engineering program. Dr. Bryan reviewed the book from an educational perspective, and provided some excellent suggestions.

I would like to thank Doug Carpenter and Steven Olenick of Combustion Science and Engineering, Inc. for providing the information on CFD Field Fire Models, which is presented in Chapter 5, Exposure Profile Modeling.

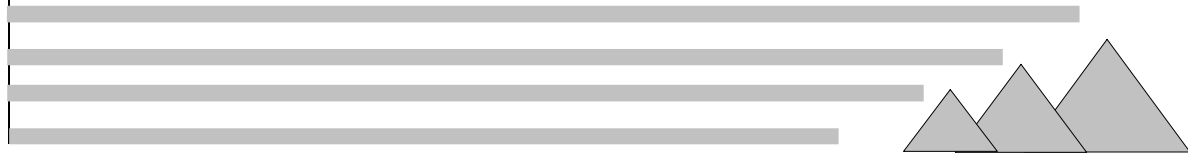
I would like to thank the management at HSB Professional Loss Control, Inc. specifically Mike Mowrer, Harvey Goranson, and Wayne Holmes, for sponsoring and supporting fire and explosion risk assessment seminars. These seminars helped formalize the risk-informed steps described in this book.

Special thanks go to Judy Ceccucci who performed typing, editing, and graphics work. Without Judy's professionalism, perseverance, and positive attitude this book could not have been completed. Thanks to Melissa Sherrod for doing an outstanding job on the grammatical editing of this book. I would also like to thank my son, Christopher, who designed the book cover and many of the graphics in the book. Chris is also the web designer for www.fireriskforum.com.

I would like to thank the PLC Educational Foundation for providing financial support towards the development and printing of this book.

Last, but not least, I would like to thank my wife, Karin, for her patience, support, and encouragement throughout this long writing project.

Table of Contents



Preface	v
From the Author	vii
Acknowledgments	ix
Acronyms	xxiii

Chapter 1 – PROGRAM OBJECTIVES

1.1 INTRODUCTION	1 – 1
1.1.1 Risk Defined	1 – 2
<i>Unmitigated Risk Versus Mitigated Risk</i>	1 – 4
1.2 RISK-BASED DECISION MAKING	1 – 6
1.3 METHODOLOGY AND STEPS	1 – 9
1.3.1 Risk-Informed, Performance-Based Fire Protection Steps	1 – 12
1.3.2 Comparison with the SFPE Performance-Based Approach	1 – 18
1.4 PROJECT MANAGEMENT ISSUES	1 – 19
1.4.1 Project Definition	1 – 20
1.4.2 Project Team Selection	1 – 20
1.4.3 Resource Allocation	1 – 22
1.5 RISK COMMUNICATION	1 – 25
1.6 REFERENCES	1 – 27

Chapter 2 – RISK TOLERANCE CRITERIA

2.1 INTRODUCTION	2 – 1
2.1.1 Bottom-Up or Top-Down Approach	2 – 2
2.1.2 Risk Tolerance Objectives	2 – 3

2.2 FINANCIAL IMPACT RISK TOLERANCE	2 – 6
2.2.1 Annualized Financial Impact Risk	2 – 6
<i>Fire and Explosion Viewed as a Financial Risk</i>	2 – 6
2.3 EXPOSURE LEVEL RISK TOLERANCE	2 – 13
2.3.1 Life Safety Risk Tolerance	2 – 13
2.3.2 Business Interruption Risk Tolerance	2 – 22
2.3.3 Establishing Consequence Categories	2 – 25
<i>Property Damage</i>	2 – 26
<i>Environmental Damage</i>	2 – 26
2.3.4 Establishing Likelihoods	2 – 27
2.3.5 Discussion on Loss Expectancy	2 – 29
<i>The Move Towards Risk-Based Loss Expectancy Estimates</i>	2 – 30
2.4 SOME KEY POINTS	2 – 32
2.5 REFERENCES	2 – 33

Chapter 3 – LOSS SCENARIO DEVELOPMENT

3.1 INTRODUCTION	3 – 1
3.2 SEQUENCE OF EVENTS	3 – 2
3.2.1 Some Examples	3 – 7
3.3 EVENT TREE STRUCTURING	3 – 9
3.3.1 ETA Steps	3 – 10
3.3.2 Example Industrial Building ETA Structure	3 – 20
3.3.3 Example Exterior Exposure ETA Structure	3 – 23
3.3.4 Example Off-Site Risk ETA Structure	3 – 25
3.4 SCENARIO SCREENING	3 – 28
3.4.1 Phase 1, Extensive List of Scenarios	3 – 29
3.4.2 Phase 2, Scenario Grouping	3 – 30
3.4.3 Phase 3, Scenario Screening	3 – 34
<i>Risk Screening Approach</i>	3 – 34
<i>Risk Screening Matrix</i>	3 – 36
<i>Action Item Summary</i>	3 – 38
3.4.4 Phase 4, Selection of Scenarios for Quantitative Analysis	3 – 39
3.4.5 Fire Event Classification	3 – 39
3.5 DISCUSSION	3 – 42

<i>Site Surveys & Interviews</i>	3 – 43
<i>Historical Data Review</i>	3 – 43
3.6 REFERENCES	3 – 44

Chapter 4 – INITIATING EVENT LIKELIHOOD

4.1 INTRODUCTION	4 – 1
<i>Risk Estimation Refresher</i>	4 – 3
4.2 HISTORICAL DATA	4 – 6
<i>Plant Specific Incident Data</i>	4 – 6
4.2.1 Industry Specific Incident Data	4 – 12
<i>Example of Some Historical Data</i>	4 – 16
4.2.2 Use of Failure Rate Data	4 – 18
<i>Combining Failure Rates from Multiple Data Bases</i>	4 – 21
4.3 FAULT TREE ANALYSIS (FTA)	4 – 24
4.3.1 Fault Tree Basics	4 – 27
<i>FTA Steps</i>	4 – 29
4.3.2 Qualitative Fault Tree Structuring	4 – 35
4.3.3 FTA Computer Software	4 – 38
4.4 EQUIPMENT FAILURES	4 – 39
4.4.1 Failure Data Sources	4 – 41
<i>Plant Specific Data</i>	4 – 41
<i>Equipment Manufacturers' Data</i>	4 – 42
<i>Published Failure Rate Data</i>	4 – 43
4.4.2 Pre-Fire Mitigation Safeguards	4 – 51
<i>Emergency Control Systems</i>	4 – 52
4.4.3 Modifying Equipment Failure Rate Data	4 – 55
<i>Performance Integrity Measures (PIMs)</i>	4 – 56
<i>An Overview of Some (PIMs)</i>	4 – 57
<i>PIM Quality Scoring</i>	4 – 61
<i>Relating PIM GPA Score to Failure Point Selection</i>	4 – 65
4.5 HUMAN ERROR	4 – 68
4.5.1 Human Error Data	4 – 70
4.6 EXTERNAL EVENTS	4 – 72
4.6.1 Earthquake	4 – 73
4.6.2 Security	4 – 75

4.7	OXYGEN AVAILABILITY	4 – 75
4.7.1	Oxygen Concentration Reduction	4 – 77
	<i>Combustible Dust</i>	4 – 79
4.8	IGNITION	4 – 81
4.8.1	Ignition Fault Tree Logic	4 – 82
	<i>Ignition Surce of Sufficient Strength is Present in Exposure Zone</i>	4 – 83
4.8.2	Ignition Source Identification	4 – 85
	<i>Industry and Generic Incident Data Bases</i>	4 – 92
4.8.3	Ignition Source Strength	4 – 93
	<i>Autoignition Temperature</i>	4 – 93
	<i>Time Ignition Source is Present</i>	4 – 97
	<i>Ignition Source Control Systems</i>	4 – 98
4.8.4	Ignition Likelihood and Engineering Judgement	4 – 100
	<i>Likelihood Selection Basis</i>	4 – 102
4.8.5	Summary	4 – 105
4.9	LIKELIHOOD CATEGORIZATION	4 – 106
4.9.1	Scenario Input	4 – 109
4.9.2	Historical Data Bandwidth	4 – 110
4.9.3	Control System Reliability	4 – 111
4.9.4	Ignition Source Potential	4 – 114
4.9.5	Establishing Fire Event Frequency and Likelihood Category Ranges	4 – 114
4.9.6	Documentation	4 – 117
4.10	DISCUSSION	4 – 120
4.11	REFERENCES	4 – 122

Chapter 5 – EXPOSURE PROFILE MODELING

5.1	INTRODUCTION	5 – 1
	<i>Risk Estimation Refresher</i>	5 – 3
5.1.1	Exposure Profile Modeling Approach	5 – 4
5.2	TARGET THRESHOLD DAMAGE LIMITS	5 – 7
5.2.1	Life Safety Exposure and TDLs	5 – 9
	<i>Radiant Heat</i>	5 – 10
	<i>Convective Heat Exposure</i>	5 – 11
	<i>Effects of Oxygen Depletion</i>	5 – 13

	<i>Toxic Products of Combustion</i>	5 – 13
	<i>Visibility Through Smoke</i>	5 – 15
5.2.2	Property Threshold Damage Limits	5 – 15
	<i>Equipment</i>	5 – 16
	<i>Stock</i>	5 – 17
	<i>Structures</i>	5 – 18
	<i>Radiant Heat Exposure</i>	5 – 19
	<i>Electrical Cables</i>	5 – 23
	<i>Electronic Equipment</i>	5 – 24
	<i>Glass</i>	5 – 24
	<i>Steel</i>	5 – 25
	<i>Concrete</i>	5 – 27
	<i>Example TDL Worksheet</i>	5 – 28
	<i>Modeling and Computer Simulation</i>	5 – 29
5.2.3	Explosion Overpressure Effects	5 – 33
5.3	TIME LINE PARAMETERS AND CONSEQUENCE LEVELS	5 – 37
5.3.1	Evaluating System Functional Requirements	5 – 37
5.3.2	Modeling Fire Source Intensity	5 – 40
	<i>Exposure to Target Subsystems</i>	5 – 40
	<i>Exposure to Control Room Operator</i>	5 – 42
	<i>Exposure to Control Room Equipment</i>	5 – 45
5.3.3	Damage Limiting Conditions and Time Line Parameters	5 – 48
5.3.4	Categorizing Event Tree Consequence Levels	5 – 53
	<i>Life Safety</i>	5 – 53
	<i>Evasive Action</i>	5 – 56
	<i>Property Damage</i>	5 – 57
	<i>Business Interruption</i>	5 – 60
	<i>Environmental Damage</i>	5 – 64
5.4	COMPARTMENT FIRE MODELS	5 – 66
5.4.1	Source → Pathway → Target	5 – 66
5.4.2	Some Fire Calculation Concepts	5 – 70
	<i>Flame Height</i>	5 – 71
	<i>Fire Plume/Ceiling Jet Correlations</i>	5 – 72
5.4.3	Zone Fire Models	5 – 74
5.4.4	Issues and Limitations of Zone Fire Models	5 – 76
5.4.5	Field Fire Models	5 – 77
	<i>Summary</i>	5 – 83
5.5	INITIAL HEAT RELEASE RATE EVALUATION	5 – 84
5.5.1	Initial Fuel Source	5 – 85

5.5.2	Fire Growth of Initial Fuel Package	5 – 88
	<i>t² Fire Uncertainty Issues</i>	5 – 90
5.5.3	Peak HRR of the Initial Fuel Package	5 – 90
	<i>Estimating Pool Fire Diameters for Unconfined Spills</i>	5 – 93
	<i>Fire Burning Time</i>	5 – 95
	<i>Torch Fires</i>	5 – 95
5.5.4	Solid Material HRR	5 – 96
5.5.5	Peak HRR Importance	5 – 99
5.6	SECONDARY FUEL SOURCES	5 – 100
5.6.1	Radiant Heat Exposure	5 – 101
	<i>Solid Flame Radiation Model</i>	5 – 104
5.7	SPECIAL HAZARD EXPOSURE MODELING	5 – 109
5.7.1	Characterize the Release	5 – 110
5.7.2	Incident Outcomes	5 – 112
	<i>Ignition</i>	5 – 114
	<i>Blast Wave Generation</i>	5 – 116
	<i>Flame Impingement</i>	5 – 117
5.7.3	Exposure Modeling	5 – 117
	<i>Torch Fire</i>	5 – 117
	<i>BLEVE</i>	5 – 119
	<i>Flash Fire Exposure</i>	5 – 120
	<i>Vapor Cloud Explosion Exposure</i>	5 – 121
5.7.4	Relating Consequence Levels	5 – 122
	<i>Computerized Models</i>	5 – 126
5.8	DISCUSSION	5 – 127
5.9	REFERENCES	5 – 129
	<i>References for Table 5.39, A Listing of Some Field Fire Models, Chap. 5</i>	5 – 132

Chapter 6 – Fire Protection System Performance Success Probability

6.1	INTRODUCTION	6 – 1
	<i>Risk Estimation Refresher</i>	6 – 3
6.1.1	The Performance Concept	6 – 4
6.1.2	Performance Measures	6 – 7
	<i>Success Tree Analysis</i>	6 – 9
6.1.3	Modeling Framework	6 – 16

6.2	RESPONSE EFFECTIVENESS	6 – 18
6.2.1	Design Application Basis	6 – 18
6.2.2	Suitability	6 – 20
	<i>Detection Systems</i>	6 – 21
	<i>Emergency Control Systems</i>	6 – 21
	<i>Fire Suppression Systems</i>	6 – 22
6.2.3	Capacity Effectiveness	6 – 23
6.2.4	Duration	6 – 26
6.2.5	Probability	6 – 27
6.2.6	System Response Time	6 – 28
	<i>Refresher</i>	6 – 29
6.2.7	FPS Response Time Evaluation Methods	6 – 34
	<i>Deterministic Modeling</i>	6 – 34
6.2.8	SRT Probability Selection	6 – 35
	<i>Explosion Suppression Systems</i>	6 – 37
	<i>Summary</i>	6 – 38
6.3	ON-LINE AVAILABILITY	6 – 39
	<i>Performance Measures</i>	6 – 41
6.3.1	Off-Line Due To Inspection, Maintenance, Proof Testing	6 – 42
6.3.2	Off-Line Due To False Trips	6 – 43
6.3.3	Off-Line Due To “Other” Conditions	6 – 44
	<i>Adverse Weather Conditions</i>	6 – 44
	<i>Unscheduled Repairs</i>	6 – 45
6.4	OPERATIONAL RELIABILITY EVALUATION LOGIC	6 – 45
6.4.1	Qualitative Logic Structuring	6 – 49
	<i>Automatic Detection Systems</i>	6 – 51
	<i>Emergency Control Systems (ECS)</i>	6 – 53
	<i>Water-Based Fire Suppression Systems</i>	6 – 58
	<i>Fire Barriers</i>	6 – 61
6.4.2	Operational Reliability (OPR) and Common Cause Failures (CCFs)	6 – 64
	<i>Internal Design-Related Failure Potential</i>	6 – 65
6.5	OPERATIONAL RELIABILITY QUANTIFICATION	6 – 67
6.5.1	Probability Documentation Table	6 – 68
	<i>Description</i>	6 – 68
	<i>Mean Failure Rate</i>	6 – 68
6.5.2	Performance Integrity Measure (PIM) Failure Rate Adjustment	6 – 72
	<i>General Design Standards</i>	6 – 75
	<i>Life-Cycle (Age)</i>	6 – 75
	<i>Management of Change (MOC) Program</i>	6 – 76

<i>Inspection and Maintenance Programs</i>	6 – 76
<i>Proof Testing</i>	6 – 76
<i>Operating Environment</i>	6 – 79
<i>Redundancy</i>	6 – 79
<i>Diagnostics (Fault Detection Capability)</i>	6 – 79
<i>Performance Integrity Measure (PIM) Quality Scoring</i>	6 – 80
<i>Importance</i>	6 – 80
6.5.3 Failure Data Sources	6 – 89
<i>Plant Specific Data</i>	6 – 89
<i>Equipment Manufacturers Data</i>	6 – 91
<i>Published Failure Rate Data</i>	6 – 92
<i>Equipment Boundaries</i>	6 – 94
<i>Failure Mode Definition</i>	6 – 94
6.6 REDUNDANCY AND INADVERTENT OPERATION	6 – 98
6.6.1 Redundant or Back-Up Equipment	6 – 98
6.6.2 Inadvertent Operation	6 – 101
<i>Inadvertent Operation Data</i>	6 – 103
6.7 MANUAL INTERVENTION	6 – 104
6.7.1 Performance Evaluation Factors	6 – 106
<i>Design Application Basis (DAB)</i>	6 – 106
<i>Availability</i>	6 – 107
<i>Human Response Failure</i>	6 – 108
<i>The Reduction of Manual Intervention, Human Error</i>	6 – 110
6.7.2 Fire Fighting	6 – 111
6.8 PERFORMANCE INTEGRITY-BASED RELIABILITY LEVELS	6 – 114
6.8.1 Review of Applicable Design Codes, Standards, Practices	6 – 115
6.8.2 Reliability Data Review	6 – 116
6.8.3 Quality Scoring of FPS Performance Integrity Measures	6 – 117
6.8.4 FPS Reliability Estimate	6 – 117
6.9 Discussion	6 – 119
<i>Fire Protection System Interfaces</i>	6 – 120
<i>Use of a Computer Program Model</i>	6 – 121
<i>Performance and Risk Management</i>	6 – 122
<i>Summary</i>	6 – 122
6.10 REFERENCES	6 – 123

Chapter 7 – RISK ESTIMATION AND COMPARISON

7.1 INTRODUCTION	7 – 1
<i>Risk Estimation Refresher</i>	7 – 2
7.2 RISK CALCULATION	7 – 3
7.2.1 Branch Line Probabilities	7 – 3
7.2.2 Aggregate Equivalent Monetary Values	7 – 6
<i>Property Damage</i>	7 – 8
<i>Business Interruption</i>	7 – 11
<i>Life Safety Exposure</i>	7 – 13
<i>Environmental Damage</i>	7 – 15
<i>Other Consequence Considerations</i>	7 – 16
7.2.3 Annualized Risk	7 – 17
<i>Total Annualized Risk</i>	7 – 19
<i>Annualized Risk Grouped by Loss Expectancy Scenarios of Interest</i>	7 – 19
<i>Likelihood of Exceeding a Defined Consequence Level</i>	7 – 21
<i>Risk Summation</i>	7 – 23
7.3 RISK COMPARISON	7 – 26
<i>Comparison with the Total Annualized Risk Estimate</i>	7 – 26
<i>Comparison with Loss Expectancy Risk Tolerance Profile</i>	7 – 27
<i>Likelihood of Exceeding a Defined Consequence Level</i>	7 – 28
<i>Life Safety Risk Comparison</i>	7 – 29
<i>Individual Risk Contours</i>	7 – 30
7.4 RISK UNCERTAINTY	7 – 31
<i>Interactive Team Reviews</i>	7 – 31
<i>Documentation</i>	7 – 34
7.4.1 Computer Spreadsheet Modeling	7 – 37
<i>What-If Analysis Versus Monte Carlo Simulation</i>	7 – 37
7.4.2 Monte Carlo Simulation	7 – 40
<i>Random Variables and Probability Distribution</i>	7 – 42
<i>A Short Example</i>	7 – 43
<i>Assigning RNG Probability Distributions</i>	7 – 44
<i>Summary</i>	7 – 52
7.5 REFERENCES	7 – 52

Chapter 8 – COST/BENEFIT ANALYSIS OF RISK REDUCTION ALTERNATIVES

8.1 INTRODUCTION	8 – 1
<i>Weak Links and Brain-Storming</i>	8 – 2
8.2 REDUCING INITIATING EVENT LIKELIHOOD	8 – 6
8.2.1 Evaluating Likelihood Reduction	8 – 9
8.2.2 Evaluate the Feasibility of Likelihood Reduction Options	8 – 11
8.2.3 Operator Error	8 – 14
8.2.4 Ignition Likelihood	8 – 18
8.2.5 Quantification of Likelihood Modifications	8 – 20
8.3 FIRE PROTECTION SYSTEM PERFORMANCE IMPROVEMENT	8 – 23
8.3.1 Improving Performance Success of a Water Spray System	8 – 30
<i>Design Application Basis</i>	8 – 31
<i>System Response Time</i>	8 – 33
<i>On-Line Availability</i>	8 – 35
<i>Operational Reliability</i>	8 – 36
<i>Operational Reliability – Performance Integrity Measures</i>	8 – 38
<i>Relating PIM Scores to Failure-On-Demand Probability</i>	8 – 40
<i>Existing Water Spray System – Opportunities for Improvement</i>	8 – 46
8.4 CONSEQUENCE MODIFICATION	8 – 50
8.4.1 Material Substitution	8 – 50
<i>Combustible Solids</i>	8 – 58
8.4.2 Modify Life Safety Exposure Levels	8 – 58
8.4.3 Modify Business Interruption (BI) Impact Levels	8 – 63
8.5 COST/BENEFIT ANALYSIS OF RISK REDUCTION ALTERNATIVES	8 – 68
8.5.1 Quantification of Risk Reduction Alternatives	8 – 68
<i>How Much Risk Reduction is Needed?</i>	8 – 68
<i>What-If Analysis</i>	8 – 71
<i>Uncertainty</i>	8 – 78
8.5.2 Cost Analysis for Selected Risk Reduction Strategies	8 – 79
8.5.3 Risk Reduction Benefit/Cost Ratios	8 – 84
<i>Benefit/Cost Ratio – Risk Reduction Strategy 4</i>	8 – 85
<i>Benefit/Cost Ratio – Risk Reduction Strategy 11</i>	8 – 86
<i>Benefit/Cost Ratio – Risk Reduction Strategy 15</i>	8 – 86
8.6 DECISION MAKING	8 – 87
<i>Decision Maker’s Preferences</i>	8 – 88

<i>Decision Analysis Tools</i>	8 – 89
<i>Analytic Hierarchy Process</i>	8 – 89
<i>“Pairwise” Comparison</i>	8 – 89
8.7 RISK MONITORING	8 – 94
8.7.1 Installation and Start-Up Risk Control	8 – 94
8.7.2 Operational Risk Monitoring	8 – 95
<i>Equipment Inspection, Maintenance, Testing (IMT) Programs</i>	8 – 96
<i>Fire Safety Self-Inspection</i>	8 – 97
8.7.3 FPS Impairments	8 – 97
<i>Assess Fire System Impairment Effects with Event Tree Analysis</i>	8 – 98
8.7.4 Performance Feedback	8 – 100
8.8 REFERENCES	8 – 101

Chapter 9 – MOVING FORWARD

9.1 INTRODUCTION	9 – 1
9.2 TAKING ACTION	9 – 3
9.3 FIRE RISK FORUM	9 – 5
9.4 REFERENCES	9 – 8
INDEX	I – 1

Acronyms



AHP	analytic hierarchy process	FMRC	Factor Mutual Research Center
AIChE	American Institute of Chemical Engineers	FOD	failure-on-demand
AIT	Auto-ignition temperature	FPS	fire protection system
ALARA	as low as reasonably achievable	FRF	Fire Risk Forum
ARB	annualized risk benefit	FTA	fault tree analysis
B/C	benefit/cost	GPA	grade point average
BI	business interruption	HAZOP	hazard and operability study
BLEVE	boiling liquid expanding vapor explosion	HCI	hydrogen chloride
BPC	basic process controls	HEP	human error probability
BPCS	basic process control system	HRA	human risk assessment
CCF	common cause failure	HRR	heat release rate
CCPS	Center for Chemical Process Safety	IEEE	Institute of Electrical and Electronics Engineers
CFD	computational fluid dynamics	IMT	inspection, maintenance, and testing
CO	carbon monoxide	IR	infrared
CPQRA	Chemical Process Quantitative Risk Analysis	ISA	Instrument Society of America
DA	decision analysis	LE	loss expectancy (analysis)
DAB	design application basis	LEL	lower explosive limit
DOE	U.S. Department of Energy	LFG	liquefied flammable gas
ECS	emergency control system	LFL	lower flammability limit
EMVs	equivalent monetary values	LNG	liquefied natural gas
ESD	emergency shutdown device	LOC	lower oxygen concentration
ESO	emergency system operation	LPG	liquefied propane gas
ESS	emergency shutdown system	MDT	mean downtime
ETA	event tree analysis	MFL	maximum foreseeable loss
EVA	expected value analysis	MOC	management of change
F&E	fire and explosion	MTBF	mean time between failures
FDS	Fire Dynamics Simulator	MTTF	mean time to failure
FHA	fire hazard analysis	MSDS	material safety and data sheets
FM	Factory Mutual	NERC	National Electric Reliability Council
FMEA	failure mode and effect analysis	NFPA	National Fire Protection Association

NLE	normal loss expectancy	S→P→T	source→pathway→target
NPRD	Nonelectric Parts Reliability Data	SFPE	Society of Fire Protection Engineers
OLA	on-line availability	SIL	safety integrity level
OPR	operational reliability	SIS	safety instrumented systems
P&IDs	pipng and instrumentation diagrams	SRT	system response time
PD	property damage	STA	success tree analysis
PIM	performance integrity measure	TDLs	threshold damage limits
PLC	programmable logic controller	TNO	Netherlands Organization for Applied Scientific Research
PML	probable maximum loss	TNT	Trinitrotoluene
QRA	quantitative risk assessment	TRC	thermal response coefficient
RAC	Reliability Analysis Center	UEL	upper explosive limit
RCM	risk- and reliability-centered maintenance	UFL	upper flammability limit
RE	response effectiveness	UV	ultraviolet
RNG	random number generation	UVCE	unconfined vapor cloud explosion
ROR	rate of return	VCE	vapor cloud explosion
RTI	response time index		
RV	replacement value		