



GUIDELINES FOR
Chemical Process
Quantitative
Risk Analysis

SECOND EDITION



A JOHN WILEY & SONS, INC., PUBLICATION



AMERICAN INSTITUTE OF
CHEMICAL ENGINEERS



CENTER FOR
CHEMICAL PROCESS SAFETY

CENTER FOR CHEMICAL PROCESS SAFETY

of the

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

3 Park Avenue

New York, New York 10016-5991

This page intentionally left blank

GUIDELINES FOR
Chemical Process
Quantitative
Risk Analysis

SECOND EDITION

This volume is one of a series of Guidelines published by the Center for Chemical Process Safety. A complete list of publications available appears at the end of this book.

GUIDELINES FOR
Chemical Process
Quantitative
Risk Analysis

SECOND EDITION



A JOHN WILEY & SONS, INC., PUBLICATION



AMERICAN INSTITUTE OF
CHEMICAL ENGINEERS



CENTER FOR CHEMICAL PROCESS SAFETY

of the

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS

3 Park Avenue

New York, New York 10016-5991

Copyright © 2000
American Institute of Chemical Engineers
3 Park Avenue
New York, New York 10016-5991

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008.

Library of Congress Cataloging-in-Publication Data

CIP data has been applied for.

ISBN: 0-8169-0720-X

PRINTED IN THE UNITED STATES OF AMERICA
10 9 8 7 6

It is sincerely hoped that the information presented in this volume will lead to an even more impressive safety record for the entire industry; however, the American Institute of Chemical Engineers, its consultants, CCPS Subcommittee members, their employers, and their employers' officers and directors disclaim making or giving any warranties or representations, express or implied, including with respect to fitness, intended purpose, use or merchantability and/or correctness or accuracy of the content of the information presented in this document and accompanying software. As between (1) American Institute of Chemical Engineers, its consultants, CCPS Subcommittee members, their employers, their employers' officers and directors and (2) the user of this document and accompanying software, the user accepts any legal liability or responsibility whatsoever for the consequences of its use or misuse.

This book is available at a special discount when ordered in bulk quantities. For information, contact the Center for Chemical Process Safety at the address shown above.

Contents

Preface	xi
Preface to the First Edition	xiii
Acknowledgments	xvii
Acknowledgments to the First Edition	xix
Management Overview	xci
Organization of the Guidelines	xxiii
Acronyms	xxv

1

Chemical Process Quantitative Risk Analysis

1.1. CPQRA Definitions	5
1.2. Component Techniques of CPQRA	7
1.2.1. Complete CPQRA Procedure	7
1.2.2. Prioritized CPQRA Procedure	13
1.3. Scope of CPQRA Studies	15
1.3.1. The Study Cube	15
1.3.2. Typical Goals of CPQRAs	18
1.4. Management of Incident Lists	19
1.4.1. Enumeration	20
1.4.2. Selection	24
1.4.3. Tracking	29
1.5. Applications of CPQRA	29
1.5.1. Screening Techniques	30
1.5.2. Applications within Existing Facilities	32
1.5.3. Applications within New Projects	32
1.6. Limitations of CPQRA	33
1.7. Current Practices	36
1.8. Utilization of CPQRA Results	38
1.9. Project Management	38

1.9.1. Study Goals	39
1.9.2. Study Objectives	39
1.9.3. Depth of Study	41
1.9.4. Special User Requirements	44
1.9.5. Construction of a Project Plan	44
1.9.6. Project Execution	50

1.10. Maintenance of Study Results 50

1.11. References 52

2

Consequence Analysis

2.1. Source Models 59

2.1.1. Discharge Rate Models	60
2.1.2. Flash and Evaporation	95
2.1.3. Dispersion Models	111

2.2. Explosions and Fires 153

2.2.1. Vapor Cloud Explosions (VCE)	157
2.2.2. Flash Fires	180
2.2.3. Physical Explosion	181
2.2.4. BLEVE and Fireball	204
2.2.5. Confined Explosions	217
2.2.6. Pool Fires	224
2.2.7. Jet Fires	237

2.3. Effect Models 244

2.3.1. Toxic Gas Effects	250
2.3.2. Thermal Effects	267
2.3.3. Explosion Effects	274

2.4. Evasive Actions 277

2.4.1. Background	277
2.4.2. Description	279
2.4.3. Example Problem	282
2.4.4. Discussion	282

2.5. Modeling Systems 283

2.6. References 284

3

Event Probability and Failure Frequency Analysis

3.1. Incident Frequencies from the Historical Record 297

3.1.1. Background	297
3.1.2. Description	298
3.1.3. Sample Problem	301
3.1.4. Discussion	303

3.2. Frequency Modeling Techniques 304

3.2.1. Fault Tree Analysis	304
----------------------------	-----

3.2.2. Event Tree Analysis	322
3.3. Complementary Plant-Modeling Techniques	330
3.3.1. Common Cause Failure Analysis	331
3.3.2. Human Reliability Analysis	368
3.3.3. External Events Analysis	379
3.4. References	387

4

Measurement, Calculation, and Presentation of Risk Estimates

4.1. Risk Measures	395
4.1.1. Risk Indices	396
4.1.2. Individual Risk	397
4.1.3. Societal Risk	399
4.1.4. Injury Risk Measures	399
4.2. Risk Presentation	400
4.2.1. Risk Indices	401
4.2.2. Individual Risk	402
4.2.3. Societal Risk	403
4.3. Selection of Risk Measures and Presentation Format	406
4.3.1. Selection of Risk Measures	406
4.3.2. Selection of Presentation Format	407
4.4. Risk Calculations	408
4.4.1. Individual Risk	408
4.4.2. Societal Risk	418
4.4.3. Risk Indices	423
4.4.4. General Comments	425
4.4.5. Example Risk Calculation Problem	425
4.4.6. Sample Problem Illustrating That F-N Curves Cannot Be Calculated from Individual Risk Contours.	438
4.5. Risk Uncertainty, Sensitivity, and Importance	442
4.5.1. Uncertainty	442
4.5.2. Sensitivity	450
4.5.3. Importance	451
4.6. References	452

5

Creation of CPQRA Data Base

5.1 Historical Incident Data	459
5.1.1. Types of Data	459
5.1.2. Sources	463
5.2. Process and Plant Data	464
5.2.1. Plant Layout and System Description	464
5.2.2. Ignition Sources and Data	464

5.3. Chemical Data	468
5.3.1. Types of Data	468
5.3.2. Sources	469
5.4. Environmental Data	469
5.4.1. Population Data	469
5.4.2. Meteorological Data	471
5.4.3. Geographic Data	472
5.4.4. Topographic Data	473
5.4.5. External Event Data	473
5.5. Equipment Reliability Data	475
5.5.1. Terminology	475
5.5.2. Types and Sources of Failure Rate Data	485
5.5.3. Key Factors Influencing Equipment Failure Rates	490
5.5.4. Failure Rate Adjustment Factors	497
5.5.5. Data Requirements and Estimated Accuracy	499
5.5.6. Collection and Processing of Raw Plant Data	499
5.5.7. Preparation of the CPORA Equipment Failure Rate Data Set	508
5.5.8. Sample Problem	513
5.6. Human Reliability Data	515
5.7. Use of Expert Opinions	518
5.8. References	518

6

Special Topics and Other Techniques

6.1. Domino Effects	525
6.1.1. Background	525
6.1.2. Description	526
6.1.3. Sample Problem	528
6.1.4. Discussion	528
6.2. Unavailability Analysis of Protective Systems	529
6.2.1. Background	529
6.2.2. Description	530
6.2.3. Sample Problem	535
6.2.4. Discussion	536
6.3. Reliability Analysis of Programmable Electronic Systems	537
6.3.1. Background	537
6.3.2. Description	538
6.3.3. Sample Problem	546
6.3.4. Discussion	548
6.4. Other Techniques	549
6.4.1. MORT Analysis	550
6.4.2. IFAL Analysis	550
6.4.3. Hazard Warning Structure	550
6.4.4. Markov Processes	551
6.4.5. Monte Carlo Techniques	559
6.4.6. GO Methods	559
6.4.7. Reliability Block Diagrams	560

Contents	ix
6.4.8. Cause–Consequence Analysis	560
6.4.9. Multiple Failure/Error Analysis (MFEA)	561
6.4.10. Sneak Analysis	563
6.5. References	570

7

CPQRA Application Examples

7.1. Simple/Consequence CPQRA Examples	573
7.1.1. Simple/Consequence CPQRA Characterization	573
7.1.2. Application to a New Process Unit	574
7.1.3. Application to an Existing Process Unit	575
7.2. Intermediate/Frequency CPQRA Examples	575
7.2.1. Intermediate/Frequency CPQRA Characterization	575
7.2.2. Application to a New Process Unit	576
7.2.3. Application to an Existing Process Unit	577
7.3. Complex/Risk CPQRA Examples	577
7.3.1. Complex/Risk Cpqra Characterization	577
7.3.2. Application to a New or Existing Process Unit	578
7.4. References	578

8

Case Studies

8.1. Chlorine Rail Tank Car Loading Facility	580
8.1.1. Introduction	580
8.1.2. Description	580
8.1.3. Identification, Enumeration, and Selection of Incidents	583
8.1.4. Incident Consequence Estimation	587
8.1.5. Incident Frequency Estimation	593
8.1.6. Risk Estimation	596
8.1.7. Conclusions	605
8.2. Distillation Column	605
8.2.1. Introduction	605
8.2.2. Description	606
8.2.3. Identification, Enumeration, and Selection of Incidents	609
8.2.4. Incident Consequence Estimation	612
8.2.5. Incident Frequency Estimation	619
8.2.6. Risk Estimation	625
8.2.7. Conclusions	632
8.3. References	634

9

Future Developments

9.1. Hazard Identification	636
-----------------------------------	------------

9.2. Source and Dispersion Models	636
9.2.1. Source Emission Models	636
9.2.2. Transport and Dispersion Models	637
9.2.3. Transient Plume Behavior	637
9.2.4. Concentration Fluctuations and the Time Averaging of Dispersion Plumes	637
9.2.5. Input Data Uncertainties and Model Validation	638
9.2.6. Field Experiments	638
9.2.7. Model Evaluation	638
9.3. Consequence Models	639
9.3.1. Unconfined Vapor Cloud Explosions (UVCE)	639
9.3.2. Boiling Liquid Expanding Vapor Explosions (BLEVES) and Fireballs	640
9.3.3. Pool and Jet Fires	640
9.3.4. Toxic Hazards	640
9.3.5. Human Exposure Models	641
9.4. Frequency Models	642
9.4.1. Human Factors	642
9.4.2. Electronic Systems	642
9.4.3. Failure Rate Data	644
9.5. Hazard Mitigation	645
9.6. Uncertainty Management	645
9.7. Integration of Reliability Analysis, CPQRA, and Cost-Benefit Studies	646
9.8. Summary	646
9.9. References	647
APPENDIX A: Loss-of-Containment Causes in the Chemical Industry	649
APPENDIX B: Training Programs	653
APPENDIX C: Sample Outline for CPQRA Reports	659
APPENDIX D: Minimal Cut Set Analysis	661
APPENDIX E: Approximation Methods for Quantifying Fault Trees	671
APPENDIX F: Probability Distributions, Parameters, and Terminology	689
APPENDIX G: Statistical Distributions Available for Use as Failure Rate Models	695
APPENDIX H: Errors from Assuming That Time-Related Equipment Failure Rates Are Constant	705
APPENDIX I: Data Reduction Techniques: Distribution Identification and Testing Methods	709
APPENDIX J: Procedure for Combining Available Generic and Plant-Specific Data	717
Conversion Factors	721
Glossary	725
Index	739

Preface

The American Institute of Chemical Engineers (AIChE) has a long history of involvement with process safety and loss control for the chemical and petrochemical industries. Through its strong ties with process designers, constructors, operators, safety professionals, and academia, the AIChE has enhanced communications and fostered improvement in the high safety standards of the industry. AIChE publications and symposia are an important resource for the chemical engineering profession on the causes of accidents and means of prevention.

The Center for Chemical Process Safety (CCPS) was established in 1985 by the AIChE to develop and disseminate technical information for use in the prevention of chemical process accidents. The Center is supported by nearly 100 organizations, including oil and chemical companies, engineering design and construction companies, engineering consultants, universities, and government agencies, which are associated with the chemical processing industries. Since its founding, the CCPS has sponsored numerous symposia, organized and sponsored research in process safety related areas, and published an extensive series of "Guidelines" books which are regarded as a primary source of process safety information.

One of the early "Guidelines" books was the *Guidelines for Chemical Process Quantitative Risk Analysis (CPQRA Guidelines)*, published in 1989. This book was intended to provide a complete overview of the tools and techniques required to do a quantitative analysis of the risk associated with the immediate impact of potential episodic accident events such as fires, explosions, and the release of acutely toxic material. The book was directed toward the analysis of acute hazards, not chronic health effects. The *CPQRA Guidelines* is part of a series of "Guidelines" books which address process hazard identification and analysis, risk assessment, and risk decision making. Related CCPS books include:

- *Guidelines for Process Equipment Reliability Data* (1989)
- *Guidelines for Hazard Evaluation Procedures, 2nd Edition with Worked Examples* (1992)
- *Guidelines for Preventing Human Error in Process Safety* (1994)
- *Tools for Making Acute Risk Decisions with Chemical Process Safety Applications* (1995)
- *Guidelines for Transportation Risk Analysis* (1995)

Since its original publication in 1989, the *CPQRA Guidelines* has been a primary resource for those in the chemical industry who use quantitative risk analysis as a risk management tool. In 1995, the CCPS Risk Analysis Subcommittee decided that there had been sufficient advances in the technology of risk analysis that an updated edition was appropriate. This update is intended to:

- Provide more detail on selected techniques than available in the original edition
- Update the models based on improvements in modeling technology
- Provide more worked examples
- Provide spreadsheet implementation of the consequence analysis examples, available on a disk.

Since the publication of the original *CPQRA Guidelines* in 1989, much has occurred in the area of consequence models, the topic of Chapter 2. For this reason, the most significant changes in the second edition will be found in Chapter 2. The revision provides more detail on consequence models, including more models and a more complete presentation on the fundamental basis, updates the models based on improvements and experience in modeling technology, and provides more worked examples. All of the worked examples in Chapter 2 have also been provided with spreadsheet solutions in a disk included with this book.

The outline of the original book, including Chapter 2 was maintained, with the exception that a separate section on jet fire models was included in Chapter 2. The sections in the revised book retain the structure of the original. Each modeling section in Chapter 2 contains a presentation of the purpose, philosophy, applications, description of the technique, a logic diagram, theoretical foundation, input requirements and availability, output, simplified approaches, and sample problems. A discussion section for each modeling section contains a presentation on strengths and weaknesses, identification and treatment of possible errors, utility, resources needed, and available computer codes.

The other chapters of the book have also been updated significantly, but less extensively. Chapter 1, describing the overall framework of CPQRA, has been updated, and some discussion of risk guidelines and criteria have been incorporated. Chapter 2 (Consequence Analysis) has been extensively rewritten and expanded as described above. In Chapter 3 (Frequency Analysis), the section on common cause failure has been updated to incorporate new techniques and methods. New worked examples have been added to Chapter 4 (Risk Calculation) to illustrate risk calculation techniques, and the chapter discusses the calculation of "Aggregate Risk", as used in API 752 (1995), "Management of Hazards Associated with Location of Process Plant Buildings." Chapter 5 (CPQRA Data) has been updated to include current information on sources of data required for a CPQRA. A discussion of "Sneak Analysis" has been added to Chapter 6 (Special Topics), and the discussion of Markov Analysis has been expanded. The example problems in Chapter 8 have been reworked, to correct some minor mathematical errors and use more accurate estimates of the impact area of the incidents considered. Chapter 9, on future research needs, has been updated, and a brief discussion of software safety has been added. The Appendices are essentially unchanged.

Preface to the First Edition

The American Institute of Chemical Engineers (AIChE) has a 30-year history of involvement with process safety and loss control for chemical and petrochemical plants. Through its strong ties with process designers, constructors, operators, safety professionals, and academia, the AIChE has enhanced communication and fostered improvement in the high safety standards of the industry. AIChE publications and symposia have become an information resource for the chemical engineering profession on the causes of accidents and means of prevention.

The Center for Chemical Process Safety (CCPS) was established in 1985 by the AIChE to develop and disseminate technical information for use in the prevention of major chemical accidents. The Center is supported by over 60 industrial sponsors in the chemical process industry (CPI), who provide the necessary funding and professional guidance to its technical committees. Since its founding, CCPS has published four volumes in its *Guidelines* series.

- *Guidelines for Hazard Evaluation Procedures* (hereafter referred to as *HEP Guidelines*) addresses method of identifying, assessing, and reducing hazards.
- *Guidelines for Use of Vapor Cloud Dispersion Models* (hereafter referred to as *VCDM Guidelines*) surveys the current (at the time of publication) vapor cloud dispersion models, shows how to use them, and discusses their strengths and weaknesses.
- *Guidelines for Safe Storage and Handling of High Toxic Hazard Materials* (hereafter referred to as *SHTM Guidelines*) discusses techniques that are used to minimize releases of high toxic hazard vapors. The presentation ranges from improving the inherent safety of the process to improving the reliability of piping and vessels.
- *Guidelines for Vapor Release Mitigation* (hereafter referred to as *VRM Guidelines*) discusses the techniques that are used to mitigate vapor releases from venting, equipment failure, etc.

The *Guidelines for Chemical Process Quantitative Risk Analysis* (hereafter referred to as *CPQRA Guidelines*) builds on the *Guidelines for Hazard Evaluation Procedures* to show the engineer how to make quantitative risk estimates for the hazards identified by the techniques given in that volume. A companion book, *Guidelines for Process Equipment*

Reliability Data (hereafter referred to as *PERD Guidelines*), is expected to be issued concurrently.

The CPI has developed a format and scope for quantitative risk analysis distinct from that used elsewhere (e.g., in the nuclear industry's Probabilistic Risk Assessments). To emphasize the distinction, this volume uses the term "Chemical Process Quantitative Risk Analysis" (CPQRA) for the methodology covered herein.

Before discussing this volume, it should be noted that the primary goal of CPQRA is to provide tools for reducing high risks in chemical plants handling hazardous materials. In applying these tools to a specific operation, appropriate management actions, based on results from a CPQRA study, help to make facilities handling hazardous chemicals safer. That is, quantitative estimates of risk allow major risk contributors to be identified and the effectiveness of various risk reduction measures to be determined. They also give guidance to the facility and to its neighbors in evaluating emergency response plans. CPQRA may also highlight areas that require attention in risk management programs.

Process releases are sometimes classified into four groups: continuous process vents, fugitive losses, emergency relief vents, and emergency unplanned episodic releases. This book is directed only toward the analysis of acute hazards represented by the last two groups of releases. It does not consider chronic health effects.

Similar in some respects to a discounted cash flow analysis, CPQRA provides an estimate of future performance. The estimate's uncertainty is directly proportional to the depth and detail for the calculation and quality of data available and used. Whereas a discounted cash flow deals with estimates with accuracy of $\pm 15\%$, CPQRA estimates have much greater uncertainty, typically one or more orders of magnitude. Given the infinite number of potential incidents, insufficient data, limited resources, and inherent uncertainties, an in-depth CPQRA cannot be accomplished for most of the industry's plant, processes, operating systems, and equipment. This book explains procedures to select from a wide range of methods—from relatively simple to progressively more complex—the CPQRA techniques that are appropriate to prepare the risk estimate required.

The *CPQRA Guidelines* provide the following:

- For process engineers, a guidance for CPQRA techniques, so they can understand the terminology, communicate with risk analysts, perform a simple CPQRA study, and understand and present the results.
- An overview of CPQRA so that senior management, unit and project management, and practicing chemical engineers can understand how risk estimates are developed, their uncertainty and limitations, and how to interpret and use the results.
- For unit and project management, a guide to the utility of CPQRA, the likely complexity of the study, the resources needed, and appropriate use at different stages of facility life.

Careful study of the material in this book can produce only a *basic* level of competence. Furthermore, the reader must recognize CPQRA does not provide exact answers; inadequacies in the data and the models lead to uncertainty in the results. The engineer who needs a deeper understanding of the discipline can consult the literature

listed in the References and Bibliography, and can consider formal training such as that listed in Appendix B.

In this volume, CCPS has endeavored—through text, worked examples, and case studies—to make the reader aware of the potential of CPQRA and its component techniques. Techniques have been selected that permit an adequate estimate of risk to be obtained with a reasonable amount of effort. Although future improvements in models and data are probable, the general methodology (as presented herein) is not likely to change significantly.

Because of the comprehensiveness and complexity of the *CPQRA Guidelines*, there may be some inconsistencies, errors, etc. in this book. The reader's comments, suggestions for improvements, and supporting rationale on deficiencies or errors are welcomed. These will be collected, reviewed, and made public immediately (where warranted) or during the next revision of the book. Please direct any comments on these *Guidelines* to

AIChE/CCPS

Attention: *CPQRA Guidelines*

3 Park Avenue

New York, NY 10016-5991

This page intentionally left blank

Acknowledgments

The *Guidelines for Chemical Process Quantitative Risk Analysis, Second Edition (CPQRA Guidelines)* has been updated from the initial 1989 edition under the guidance of the Center for Chemical Process Safety (CCPS) Risk Assessment Subcommittee (RASC). Most of the material from the initial (1989) edition of the book, which was written by the 1989 RASC members, Technica, Inc. (now DNV Technica), and several other contributors, remains in this edition. The contributions of the original edition authors are listed in the "Acknowledgments to the First Edition."

Writing of new material for the Second Edition and updating and revision of the original text of the *CPQRA Guidelines* was done by the RASC and with the aid of several other authors. The RASC was chaired by Dennis C. Hendershot (Rohm and Haas Company), and the RASC members include Brian R. Dunbobbin and Walter Silowka (Air Products and Chemicals, Inc.), Arthur G. Mundt (Dow Chemical), William Tilton (DuPont), Scott Ostrowski (ExxonMobil Chemical), Donald L. Winter (Mobil), Raymond A. Freeman (Solutia), Arthur Woltman (Shell), Thomas Janicik (Solvay Polymers), Richard M. Gustafson (Texaco), William K. Lutz (Union Carbide), Chuck Fryman (FMC), Della Wong (Nova Chemicals, Ltd.), Felix Freiheiter and Thomas Gibson (Center for Chemical Process Safety).

The RASC particularly recognizes the major contribution of Dr. Daniel A. Crowl of Michigan Technological University, for extensively revising Chapter 2 (Consequence Analysis) of this book, including the addition of a large amount of new and original material. Dr. Crowl also developed the set of Chapter 2 example problems and spreadsheet solutions which are included with the book, and provided oversight for the revisions to the example problems in Chapter 8.

Other volunteer authors also made major contributions to this edition:

- Dr. Henrique Paula of JBF Associates provided the revised discussion of common cause failure in Section 3.3.1.
- Mr. Paris Stavrianidis of Factory Mutual Research revised the discussion of Markov Analysis in Chapter 6.
- Mr. James Vogas of Boeing Aerospace Operations provided the discussion of Sneak Analysis in Chapter 6.
- Mr. Robert Charette of Itabhi Corporation contributed the discussion of software safety in Chapter 9

- Mr. Chad Mashuga of Michigan Technological University revised and updated calculations in the example problems in Chapter 8, and also updated and improved the text, figures, and tables.

The RASC also thanks the CCPS management and staff for their support of this project, including Mr. Bob Perry, Dr. Jack Weaver, and Mr. Les Wittenberg. The RASC also thanks the following for their peer review of *CPQRA Guidelines, Second Edition*:

Sanjeev Mohindra, Arthur D. Little, Inc.
Henry Ozog, Arthur D. Little, Inc.
Kenneth H. Harrington, Battelle Memorial Institute
James L. Paul, Celanese
Jack Philley, DNV
David W. Jones, EQE International
Walter L. Frank, EQE International
Adrian Garcia, FMC Corp.
John A. Hoffmeister, Lockheed Martin Energy Systems, Inc.
Jan C. Windhorst, Nova Chemicals, Ltd.
Willard C. Gekler, PLG, Inc.
Paul Baybutt, Primatech, Inc.
Peter Fletcher, Raytheon Engineers & Constructors, Inc.
Gerard Opschoor, TNO Prins Maurits Laboratorium
Ken Murphy, U.S. Department of Energy
Jim Lightner, Westinghouse Savannah River Co.

The RASC dedicates this book to two of our friends and colleagues, Mr. Donald L. Winter of Mobil Oil Corporation, and Mr. Felix Freiheiter of the Center for Chemical Process Staff. Both were significant contributors to the Second Edition, and to the many other activities of the CCPS Risk Assessment Subcommittee for many years. Mr. Winter unfortunately passed away due to a sudden illness during the later stages of the writing of the book. Mr. Freiheiter also passed away as the book was being prepared for publication. Their influence can be found throughout the book.

Acknowledgments to the First Edition

This volume was written jointly by the CCPS Risk Assessment Subcommittee and Technica, Inc. The CCPS Subcommittee was chaired by R. W. Ormsby (Air Products and Chemicals), and included (in alphabetical order); R. E. DeHart, II (Union Carbide), H. H. Feng (ICI Americas, formerly of Stauffer Chemical), R. A. Freeman (Monsanto), S. B. Gibson (du Pont), D. C. Hendershot (Rohm and Haas), C. A. Master (Fluor Daniel), R. F. Schwab (Allied-Signal), and J. C. Sweeney (ARCO Chemical). T. W. Carmody, F. Freiheiter, R. G. Hill, and L. H. Wittenberg of CCPS provided staff support. The Technica Team was directed by D. H. Slater and managed by R. M. Pitblado. The Technica team included B. Morgan, A. Shafaghi, L. G. Bacon, M. A. Seaman, L. J. Bellamy, S. R. Harris, P. Baybutt, D. M. Boulton, and N. C. Harris. F. P. Lees (University of Loughborough) reviewed an early draft of the document and his comments are gratefully acknowledged. The substantial contributions of the employer organizations (both in time and resources) of the Subcommittee and of Technica are gratefully acknowledged.

An acknowledgment is also made to JBF Associates, Inc. (J. S. Arendt, D. F. Montague, H. M. Paula, L. E. Palko) for their preparation of the subsection on common cause failure analysis (Section 3.3.1) and inclusion of additional material in the section on fault tree analysis (Section 3.2.1), and to Meridian Corporation (C. O. Schultz and W. S. Perry) for the preparation of the section on toxic gas effects (Section 2.3.1).

Two specific individuals should also be acknowledged for significant contributions: C. W. Thurston of Union Carbide for assistance in the preparation of the subsection on programmable electronic systems (Section 6.3) and G. K. Lee of Air Products and Chemicals who assisted in the preparation of the subsections addressing discharge rates, flash and evaporation, and dispersion (Sections 2.1.1., 2.1.2, and 2.1.3).

Finally, the CCPS Risk Assessment Subcommittee wishes to express its sincere gratitude to Dr. Elisabeth M. Drake for reviewing the final manuscript and her many helpful comments and suggestions.

This page intentionally left blank

Management Overview

Risk analysis methodology has been applied to various modern technologies such as aerospace, electronics, and nuclear power. Over the last 15 years this methodology has been adapted to the particular needs of the CPI. The Center for Chemical Process Safety (CCPS) of AIChE has developed this book to provide a guidance manual for the application of this methodology. The term “Chemical Process Quantitative Risk Analysis” (CPQRA) is used to emphasize the unique character of this methodology as applied to the CPI.

CPQRA identifies those areas where operations, engineering, or management systems may be modified to reduce risk, and may identify the most economical way to do it. It can be applied in the initial siting and design of the facility and during its entire life. The primary goal of CPQRA is that appropriate management actions, based on results from a CPQRA study, help to make facilities handling hazardous chemicals safer.

CPQRA is one component of an organization’s total risk management. It allows the quantitative analysis of risk alternatives that can be balanced against other considerations. Management can then make more informed, cost-effective decisions on the allocation of resources for risk reduction. The reader is reminded that the AIChE/CCPS publication *A Challenge to Commitment* strongly encourages CPI management to have an effective, comprehensive process safety and risk management program.

CPQRA can be applied at any stage in the life of a facility. The depth of study may vary depending on the objectives and information available. Maximum benefits result when CPQRA is applied at the beginning (conceptual and design stages) of a project and maintained throughout its life.

Although elements of a CPQRA process are being practiced today in the CPI, only a few organizations have integrated this process into their risk management program. However, application of CPQRA is becoming more widespread and may become an integral part of more companies’ risk management programs. The reason that these methods are not in more widespread use is that detailed CPQRA techniques are complex and cost intensive, and require special resources and trained personnel. Also, CPQRA techniques have not been well understood and described in the literature. However, an investment in CPQRA often pays tangible returns in identifying cost effective process or operational improvements.

The philosophy behind this volume is to provide an introduction to CPQRA methodology in sufficient depth so that a process engineer with some practice can undertake simple CPQRA studies with minimal outside assistance. The engineer should be able to

1. respond to a request for a risk assessment;
2. convert the request into a definable study objective;
3. develop a scope of work;
4. understand the types of data and sources of information required;
5. estimate the time and costs for the study;
6. calculate the results;
7. analyze the results for reasonableness;
8. present the results in a useful format.

The careful definition of scope and depth of study in the application of CPQRA is crucial to success because it is cost and resource intensive. Detailed CPQRA should be used sparingly and only to that depth of study necessary to achieve a study's goals and objectives. If not properly controlled, even a simple CPQRA can generate an unmanageable calculation burden.

Careful study of the material in these guidelines can produce only a basic level of competence. Supplementary review of important references and training is essential. This book is directed toward the assessment of episodic, short-term hazards rather than chronic health hazards. Discussion of regulatory issues, public risk perception, risk criteria, and acceptable risk are excluded.

Finally, it should be thoroughly understood that CPQRA methodology is a sophisticated analysis tool that requires fundamental assumptions about the management and maintenance systems and process safety programs in place at a given facility. Unless management is committed to process safety and has those necessary support programs in place, use of a CPQRA is futile. However, with this support, CPQRA can be a valuable complementary tool to improving safety in a chemical plant.

Organization of the Guidelines

This volume provides an introduction to the techniques of CPQRA in sufficient detail that process engineers, not specifically trained in this technology, should be able to undertake elementary risk analysis studies. Numerous worked examples and case studies have been provided to illustrate each component technique. A comprehensive bibliography provides references to more advanced topics.

Chapter 1 describes the broad framework of CPQRA, its component techniques, and current practices.

Chapter 2 summarizes quantitative techniques used for consequence analysis, including physical models for fire, explosions, and dispersion of flammable or toxic materials (Sections 2.1 and 2.2). Human health effects and structural damage are reviewed (Section 2.3), along with evasive actions (Section 2.4) such as shelter, escape, and evacuation.

Chapter 3 reviews quantitative techniques for estimating incident frequency, including the historical record (Section 3.1), fault tree analysis (Section 3.2.1) and event tree analysis (Section 3.2.2). Complementary techniques are also reviewed, including common-cause failures (Section 3.3.1), human reliability (Section 3.3.2), and external event (Section 3.3.3) analyses.

Chapter 4 provides a description of commonly used risk measures (Section 4.1), their forms of presentation (Section 4.2), guidelines for their selection (Section 4.3), and methods for their calculation (Section 4.4). Importance, uncertainty, and sensitivity factors are also addressed (Section 4.5).

Chapter 5 discusses data sources used in CPQRA, including historical incident data (Section 5.1), process and plant data (Section 5.2), chemical data (Section 5.3), environmental data (Section 5.4), equipment reliability data (Section 5.5), human reliability data (Section 5.6), and the use of expert opinion (Section 5.7).

Chapter 6 reviews, briefly, several topics that are relevant to CPQRA, including domino effects (Section 6.1), unavailability of protective systems (Section 6.2), reliability of programmable electronic systems (Section 6.3), and other techniques (Section 6.4).

Chapter 7 addresses the application and utilization of CPQRA results, for examples ranging from the simple to the complex.

Chapter 8 provides two case studies to demonstrate the application of CPQRA techniques. The first case study of a railcar loading terminal (Section 8.1) is designed to

use manual calculation techniques. The second case study, a hydrocarbon distillation column (Section 8.2), employs slightly more sophisticated modeling techniques.

Chapter 9 discusses research and development needs to improve CPQRA. Following Chapter 9, various appendices supporting the material in the text are provided.

Finally, a summary of available computer software has been provided in Chapters 2, 3, and 4, presenting models for consequence, frequency, and risk estimation, respectively.

Nomenclature and Units

The equations in the volume are from a number of disciplines and reference sources, which do not have consistent nomenclature (symbols) and units. In order to facilitate comparisons with the sources, we have used the conventions of each source, rather than impose a standard “across the board” for the volume.

Nomenclature and units are given after each equation (or set of equations) in the text. Readers are cautioned to ensure that they are using the proper values when applying these equations to their problems.

Acronyms

AAR	American Association of Railroads
ACGIH	American Conference of Governmental Industrial Hygienists
ACMH	Advisory Commission on Major Hazards
AEC	Atomic Energy Commission
AGA	American Gas Association
AICHE/CCPS	American Institute of Chemical Engineers—Center for Chemical Process Safety
AICHE-DIERS	American Institute of Chemical Engineers—Design Institute for Emergency Relief Systems
AICHE-DIPPR	American Institute of Chemical Engineers—Design Institute for Physical Property Data
AIHA	American Industrial Hygiene Association
AIT	Auto-Ignition Temperature
API	American Petroleum Institute
ARC	Accelerating Rate Calorimetry
ASEP	Accident Sequence Evaluation Program
ASME	American Society of Mechanical Engineers
ATC	Acute Toxic Concentration
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAER	Community Awareness and Emergency Response
CCF	Common Cause Failure
CCPS	Center for Chemical Process Safety
CEP	Chemical Engineering Progress
CFD	Computational Fluid Dynamics
CMA	Chemical Manufacturers Association
CONSEQ	Consequence Analysis Computer Software (DNV)
CPI	Chemical Process Industry
CPU	Computer Processing Unit
CPQRA	Chemical Process Quantitative Risk Analysis
CRC	Chemical Rubber Company
CSTR	Continuous Stirred Tank Reactor
DDCS	Distributed Digital Control System
DOE	Department of Energy

DOT	Department of Transportation
DSC	Differential Scanning Calorimeter
EEC	European Economic Community
EEGL	Emergency Exposure Guidance Level
EFCE	European Federation of Chemical Engineers
EF	Error Factor
ENF	Expected Number of Failures
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERPG	Emergency Response Planning Guidelines
ERV	Emergency Response Value
ESD	Emergency Shutdown Device
ESV	Emergency Shutdown Valve
ETA	Event Tree Analysis
EuReData	European Reliability Data Association
FAR	Fatal Accident Rate
FDT	Fractional Dead Time
FEMA	Federal Emergency Management Agency
FMEA	Failure Modes and Effects Analysis
FN	Frequency Number
FR	Failure Rate
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability
HEART	Human Error Assessment and Reduction Technique
HEP	Hazard Evaluation Procedures
HFA	Human Failure Analysis
HMSO	Her Majesty's Stationary Office
HRA	Human Reliability Analysis
HSE	Health and Safety Executive
IChemE	Institute of Chemical Engineers (Great Britain)
ICI	Imperial Chemical Industries
IDLH	Immediately Dangerous to Life and Health
IEEE	Institute of Electrical and Electronic Engineers
IFAL	Instantaneous Fractional Annual Loss
IHI	Individual Hazard Index
INPO	Institute of Nuclear Power Operations
IPRDS	In-Plant Reliability Data System
ISBN	International Standard Book Number
KTT	Kinetic Tree Theory
LC	Lethal Concentration
LCL	Lower Confidence Limit
LD	Lethal Dose
LFL	Lower Flammable Limit
LNG	Liquified Natural Gas
LOC	Level of Concern
LPG	Liquified Petroleum Gas

MAPPS	Maintenance Personnel Performance Simulation
MFEA	Multiple Failure/Error Analysis
MIL-HDBK	Department of Defense Military Handbook
MOCUS	Computer Program for Minimal Cut Set Determination
MR	Median Rank
MSDS	Material Safety Data Sheets
MORT	Management Oversight and Risk Tree Analysis
MTFB	Mean Time Between Failure
NAS	National Academy of Science
NASA	National Aeronautical and Space Administration
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NJ-DEP	New Jersey Department of Environmental Protection
NOAA	National Oceanic and Atmospheric Administration
NPRDS	Nuclear Plant Reliability Data System
NRC	National Research Council
NSC	National Safety Council
NTIS	National Technical Information Service
NTSB	National Transportation Safety Board
NUREG	Nuclear Regulatory Commission
OAT	Operator Action Tree
OREDA	Offshore Reliability Data Handbook
ORC	Organization Resources Counselors, Inc. (Washington, DC)
OSHA	Occupational Safety and Health Administration
PC	Paired Comparisons
PE	Process Engineer
PEL	Permissible Exposure Limits
PERD	Process Equipment Reliability Data
PES	Programmable Electronic System
PFD	Process Flow Diagram
PFOD	Probability of Failure on Demand
PHA	Preliminary Hazard Analysis
P&ID	Piping and Instrumentation Diagram
PV	Pressure Volume
PLC	Programmable Logic Controller
PLG	Pressurized Liquified Gas
PRA	Probabilistic Risk Assessment
RBD	Reliability Block Diagram
R & D	Research and Development
RLG	Refrigerated Liquified Gas
RMP	Risk Management Plan
ROD	Average Rate of Death
ROF	Average Rate of Failure
RSST	Reactive Systems Screening Tool
RTECS	Registry of Toxic Effect of Chemical Substances
SCRAM	Support Center Regulatory Air Models

SHTM	Storage and Handling of High Toxic Hazard Materials
SLIM-MAUD	Success Likelihood Index Methodology-Multi Attribute Utility Decomposition
SPEGL	Short Term Public Emergency Guidance Levels
SRD	Safety and Reliability Directorate (U.K. Atomic Energy Authority, Warrington, England)
SRS	System Reliability Service
STEL	Short Term Exposure Limits
SYREL	Systems Reliability Service Data Base
TCPA	Toxic Catastrophe Prevention Act
THERP	Technique for Human Error Rate Prediction
TNT	Trinitrotoluene
TLV	Threshold Limit Values
TNO	Netherlands Organization for Applied Scientific Research
TXDS	Toxicity Dispersion
UCL	Upper Confidence Limit
UFL	Upper Flammable Limit
UCSIP	Union des Chambres Syndicales de L'Industrie de Petrole
UNIDO	United Nations Industrial Development Organization
VCDM	Vapor Cloud Dispersion Modeling
VCE	Vapor Cloud Explosion
VDI	Verein Deutscher Ingenieure
VRM	Vapor Release Mitigation
VSP	Vent Sizing Package
WASH-1400	<i>Reactor Safety Study</i> (Rasmussen, 1975)
WDT	Watchdog Timer