
Contents

Preface xv

About the Authors xvii

On the Cover xviii

Nomenclature xix

1 Introduction 1

- 1-1 Safety Programs 2
- 1-2 Engineering Ethics 4
- 1-3 Accident and Loss Statistics 4
- 1-4 Acceptable Risk 12
- 1-5 Public Perceptions 14
- 1-6 The Nature of the Accident Process 15
- 1-7 Inherent Safety 20
- 1-8 Seven Significant Disasters 23
 - Flixborough, England 23
 - Bhopal, India 25
 - Seveso, Italy 26
 - Pasadena, Texas 27
 - Texas City, Texas 29
 - Jacksonville, Florida 30
 - Port Wentworth, Georgia 30
- Suggested Reading 31
- Problems 32

2 Toxicology 37

- 2-1 How Toxicants Enter Biological Organisms 38
 - Gastrointestinal Tract 39
 - Skin 39
 - Respiratory System 40
- 2-2 How Toxicants Are Eliminated from Biological Organisms 41
- 2-3 Effects of Toxicants on Biological Organisms 42
- 2-4 Toxicological Studies 43
- 2-5 Dose versus Response 44
- 2-6 Models for Dose and Response Curves 50
- 2-7 Relative Toxicity 56
- 2-8 Threshold Limit Values 56
- 2-9 National Fire Protection Association (NFPA) Diamond 58
 - On-Line Resources 59
 - Suggested Reading 60
 - Problems 60

3 Industrial Hygiene 65

- 3-1 Government Regulations 66
 - Laws and Regulations 66
 - Creating a Law 66
 - Creating a Regulation 66
 - OSHA: Process Safety Management 71
 - EPA: Risk Management Plan 73
 - DHS: Chemical Facility Anti-Terrorism Standards (CFATS) 76
- 3-2 Industrial Hygiene: Anticipation and Identification 78
 - Material Safety Data Sheets 81
- 3-3 Industrial Hygiene: Evaluation 84
 - Evaluating Exposures to Volatile Toxicants by Monitoring 84
 - Evaluating Worker Exposures to Dusts 88
 - Evaluating Worker Exposures to Noise 89
 - Estimating Worker Exposures to Toxic Vapors 91
- 3-4 Industrial Hygiene: Control 99
 - Respirators 101
 - Ventilation 103
 - On-Line Resources 109
 - Suggested Reading 109
 - Problems 110

4 Source Models 119

- 4-1 Introduction to Source Models 119
- 4-2 Flow of Liquid through a Hole 122
- 4-3 Flow of Liquid through a Hole in a Tank 126
- 4-4 Flow of Liquids through Pipes 131
 - 2-K Method 134

- 4-5 Flow of Gases or Vapors through Holes 140
- 4-6 Flow of Gases or Vapors through Pipes 146
 - Adiabatic Flows 146
 - Isothermal Flows 153
- 4-7 Flashing Liquids 163
- 4-8 Liquid Pool Evaporation or Boiling 169
- 4-9 Realistic and Worst-Case Releases 170
- 4-10 Conservative Analysis 172
 - Suggested Reading 173
 - Problems 174

5 Toxic Release and Dispersion Models 185

- 5-1 Parameters Affecting Dispersion 186
- 5-2 Neutrally Buoyant Dispersion Models 190
 - Case 1: Steady-State Continuous Point Release with No Wind 194
 - Case 2: Puff with No Wind 195
 - Case 3: Non-Steady-State Continuous Point Release with No Wind 196
 - Case 4: Steady-State Continuous Point Source Release with Wind 197
 - Case 5: Puff with No Wind and Eddy Diffusivity Is a Function of Direction 197
 - Case 6: Steady-State Continuous Point Source Release with Wind and Eddy Diffusivity Is a Function of Direction 198
 - Case 7: Puff with Wind 198
 - Case 8: Puff with No Wind and with Source on Ground 199
 - Case 9: Steady-State Plume with Source on Ground 199
 - Case 10: Continuous Steady-State Source with Source at Height H_r above the Ground 200
 - Pasquill-Gifford Model 200
 - Case 11: Puff with Instantaneous Point Source at Ground Level, Coordinates Fixed at Release Point, Constant Wind Only in x Direction with Constant Velocity u 204
 - Case 12: Plume with Continuous Steady-State Source at Ground Level and Wind Moving in x Direction at Constant Velocity u 205
 - Case 13: Plume with Continuous Steady-State Source at Height H_r above Ground Level and Wind Moving in x Direction at Constant Velocity u 206
 - Case 14: Puff with Instantaneous Point Source at Height H_r above Ground Level and a Coordinate System on the Ground That Moves with the Puff 207
 - Case 15: Puff with Instantaneous Point Source at Height H_r above Ground Level and a Coordinate System Fixed on the Ground at the Release Point 208
 - Worst-Case Conditions 208
 - Limitations to Pasquill-Gifford Dispersion Modeling 208

- 5-3 Dense Gas Dispersion 209
- 5-4 Dense Gas Transition to Neutrally Buoyant Gas 219
 - Continuous Release Transition 219
 - Continuous Release Downwind Concentration 221
 - Instantaneous Release Transition 221
 - Instantaneous Release Downwind Composition 222
- 5-5 Toxic Effect Criteria 225
- 5-6 Effect of Release Momentum and Buoyancy 233
- 5-7 Release Mitigation 234
 - Suggested Reading 235
 - Problems 236

6 Fires and Explosions 245

- 6-1 The Fire Triangle 245
- 6-2 Distinction between Fires and Explosions 247
- 6-3 Definitions 247
- 6-4 Flammability Characteristics of Liquids and Vapors 249
 - Liquids 250
 - Gases and Vapors 253
 - Vapor Mixtures 253
 - Flammability Limit Dependence on Temperature 255
 - Flammability Limit Dependence on Pressure 256
 - Estimating Flammability Limits 256
- 6-5 Limiting Oxygen Concentration and Inerting 260
- 6-6 Flammability Diagram 262
- 6-7 Ignition Energy 270
- 6-8 Autoignition 270
- 6-9 Auto-Oxidation 271
- 6-10 Adiabatic Compression 272
- 6-11 Ignition Sources 273
- 6-12 Sprays and Mists 274
- 6-13 Explosions 275
 - Detonation and Deflagration 276
 - Confined Explosions 277
 - Blast Damage Resulting from Overpressure 287
 - TNT Equivalency 291
 - TNO Multi-Energy Method 293
 - Energy of Chemical Explosions 296
 - Energy of Mechanical Explosions 298
 - Missile Damage 301
 - Blast Damage to People 301
 - Vapor Cloud Explosions 303
 - Boiling-Liquid Expanding-Vapor Explosions 304
 - Suggested Reading 304
 - Problems 305

7 Concepts to Prevent Fires and Explosions 317

- 7-1 Inerting 318
 - Vacuum Purging 318
 - Pressure Purging 321
 - Combined Pressure-Vacuum Purging 323
 - Vacuum and Pressure Purging with Impure Nitrogen 323
 - Advantages and Disadvantages of the Various Pressure and Vacuum Inerting Procedures 325
 - Sweep-Through Purging 325
 - Siphon Purging 327
 - Using the Flammability Diagram To Avoid Flammable Atmospheres 327
- 7-2 Static Electricity 333
 - Fundamentals of Static Charge 333
 - Charge Accumulation 334
 - Electrostatic Discharges 335
 - Energy from Electrostatic Discharges 337
 - Energy of Electrostatic Ignition Sources 338
 - Streaming Current 339
 - Electrostatic Voltage Drops 342
 - Energy of Charged Capacitors 342
 - Capacitance of a Body 347
 - Balance of Charges 350
- 7-3 Controlling Static Electricity 356
 - General Design Methods To Prevent Electrostatic Ignitions 357
 - Relaxation 358
 - Bonding and Grounding 358
 - Dip Pipes 359
 - Increasing Conductivity with Additives 362
 - Handling Solids without Flammable Vapors 363
 - Handling Solids with Flammable Vapors 363
- 7-4 Explosion-Proof Equipment and Instruments 363
 - Explosion-Proof Housings 365
 - Area and Material Classification 365
 - Design of an XP Area 366
- 7-5 Ventilation 367
 - Open-Air Plants 367
 - Plants Inside Buildings 368
- 7-6 Sprinkler Systems 370
- 7-7 Miscellaneous Concepts for Preventing Fires and Explosions 374
 - Suggested Reading 374
 - Problems 375

8 Chemical Reactivity 381

- 8-1 Background Understanding 382
- 8-2 Commitment, Awareness, and Identification of Reactive Chemical Hazards 384
- 8-3 Characterization of Reactive Chemical Hazards Using Calorimeters 390
 - Introduction to Reactive Hazards Calorimetry 391
 - Theoretical Analysis of Calorimeter Data 397
 - Estimation of Parameters from Calorimeter Data 408
 - Adjusting the Data for the Heat Capacity of the Sample Vessel 412
 - Heat of Reaction Data from Calorimeter Data 413
 - Using Pressure Data from the Calorimeter 414
 - Application of Calorimeter Data 415
- 8-4 Controlling Reactive Hazards 416
 - Suggested Reading 418
 - Problems 418

9 Introduction to Reliefs 429

- 9-1 Relief Concepts 430
- 9-2 Definitions 432
- 9-3 Location of Reliefs 433
- 9-4 Relief Types and Characteristics 436
 - Spring-Operated and Rupture Discs 436
 - Buckling-Pin Reliefs 440
 - Pilot-Operated Reliefs 440
 - Chatter 441
 - Advantages and Disadvantages of Various Reliefs 442
- 9-5 Relief Scenarios 443
- 9-6 Data for Sizing Reliefs 444
- 9-7 Relief Systems 444
 - Relief Installation Practices 445
 - Relief Design Considerations 447
 - Horizontal Knockout Drum 448
 - Flares 451
 - Scrubbers 452
 - Condensers 452
 - Suggested Reading 452
 - Problems 453

10 Relief Sizing 459

- 10-1 Conventional Spring-Operated Reliefs in Liquid Service 460
- 10-2 Conventional Spring-Operated Reliefs in Vapor or Gas Service 466

- 10-3 Rupture Disc Reliefs in Liquid Service 470
- 10-4 Rupture Disc Reliefs in Vapor or Gas Service 471
- 10-5 Two-Phase Flow during Runaway Reaction Relief 472
 - Simplified Nomograph Method 478
- 10-6 Pilot-Operated and Bucking-Pin Reliefs 481
- 10-7 Deflagration Venting for Dust and Vapor Explosions 481
 - Vents for Low-Pressure Structures 483
 - Vents for High-Pressure Structures 485
- 10-8 Venting for Fires External to Process Vessels 488
- 10-9 Reliefs for Thermal Expansion of Process Fluids 492
 - Suggested Reading 496
 - Problems 497

11 Hazards Identification 505

- 11-1 Process Hazards Checklists 508
- 11-2 Hazards Surveys 508
- 11-3 Hazards and Operability Studies 524
- 11-4 Safety Reviews 530
 - Informal Review 533
 - Formal Review 534
- 11-5 Other Methods 537
 - Suggested Reading 538
 - Problems 538

12 Risk Assessment 549

- 12-1 Review of Probability Theory 550
 - Interactions between Process Units 552
 - Revealed and Unrevealed Failures 558
 - Probability of Coincidence 562
 - Redundancy 564
 - Common Mode Failures 564
- 12-2 Event Trees 564
- 12-3 Fault Trees 569
 - Determining the Minimal Cut Sets 572
 - Quantitative Calculations Using the Fault Tree 575
 - Advantages and Disadvantages of Fault Trees 576
 - Relationship between Fault Trees and Event Trees 576
- 12-4 QRA and LOPA 577
 - Quantitative Risk Analysis 577
 - Layer of Protection Analysis 578
 - Consequence 581
 - Frequency 581
 - Typical LOPA 585
 - Suggested Reading 588
 - Problems 588

13 Safety Procedures and Designs 597

- 13-1 Process Safety Hierarchy 598
 - Process Safety Strategies 598
 - Layers of Protection 598
- 13-2 Managing Safety 599
 - Documentation 599
 - Communications 599
 - Delegation 599
 - Follow-up 600
- 13-3 Best Practices 600
- 13-4 Procedures—Operating 600
- 13-5 Procedures—Permits 601
 - Hot Work Permit 601
 - Lock-Tag-Try Permit 601
 - Vessel Entry Permit 602
- 13-6 Procedures—Safety Reviews and Accident Investigations 603
 - Safety Reviews 603
 - Incident Investigations 603
- 13-7 Designs for Process Safety 604
 - Inherently Safer Designs 605
 - Controls—Double Block and Bleed 606
 - Controls—Safeguards or Redundancy 607
 - Controls—Block Valves 608
 - Controls—Explosion Suppression 608
 - Flame Arrestors 608
 - Containment 609
 - Materials of Construction 610
 - Process Vessels 610
 - Deflagrations 612
 - Detonations 612
- 13-8 Miscellaneous Designs for Fires and Explosions 615
- 13-9 Designs for Runaway Reactions 615
- 13-10 Designs for Handling Dusts 616
 - Designs for Preventing Dust Explosions 617
 - Management Practices for Preventing Dust Explosions 617
 - Suggested Reading 617
 - Problems 618

14 Case Histories 621

- 14-1 Static Electricity 622
 - Tank Car Loading Explosion 622
 - Explosion in a Centrifuge 622
 - Duct System Explosion 623
 - Conductor in a Solids Storage Bin 623

	Pigment and Filter	624
	Pipefitter's Helper	624
	Lessons Learned Concerning Static Electricity	624
14-2	Chemical Reactivity	626
	Bottle of Isopropyl Ether	630
	Nitrobenzene Sulfonic Acid Decomposition	630
	Organic Oxidation	631
	Lessons Learned Concerning Chemical Reactivity	631
14-3	System Designs	631
	Ethylene Oxide Explosion	631
	Ethylene Explosion	632
	Butadiene Explosion	632
	Light Hydrocarbon Explosion	632
	Pump Vibration	633
	Pump Failure	633
	Second Ethylene Explosion	633
	Third Ethylene Explosion	634
	Second Ethylene Oxide Explosion	634
	Lessons Learned Concerning Designs	635
14-4	Procedures	637
	Leak Testing a Vessel	637
	Man Working in Vessel	638
	Vinyl Chloride Explosion	638
	Dangerous Water Expansion	638
	Phenol-Formaldehyde Runaway Reaction	639
	Conditions and Secondary Reaction Cause Explosion	639
	Fuel-Blending Tank Explosion	640
	Lessons Learned Concerning Procedures	641
14-5	Training	642
	Weld Failure	642
	Safety Culture	642
	Training within Universities	643
	Training Regarding the Use of Standards	643
	Lessons Learned Concerning Training	645
14-6	Conclusion	645
	Suggested Reading	646
	Problems	646

A Unit Conversion Constants 649

B Flammability Data for Selected Hydrocarbons 653

C Detailed Equations for Flammability Diagrams 659

Equations Useful for Gas Mixtures 659

Equations Useful for Placing Vessels into and out of Service 664

D	Formal Safety Review Report for Example 10-4	669
E	Saturation Vapor Pressure Data	679
F	Special Types of Reactive Chemicals	681
G	Hazardous Chemicals Data for a Variety of Chemical Substances	687
	Index	695