Contents

		roperties of Materials
2.1		nability
	2.1.1	Safety Parameters for Flammable Gases
		and Vapours
2.2		cally Unstable Materials: Decomposition
	and Po	olymerization
2.3	Flamm	nable Liquids
	2.3.1	Flash Point
	2.3.2	Fire Point
2.4	Dusts.	
	2.4.1	Self-Ignition
	2.4.2	Glow Temperature
	2.4.3	Explosion Limits
	2.4.4	Minimum Ignition Energy
	2.4.5	Limiting Oxygen Concentration (LOC)
	2.4.6	Maximum Pressure and Maximum Rate
		of Pressure Rise
2.5	Explos	sives
	2.5.1	Brisance
	2.5.2	Loading Density
	2.5.3	Oxygen Balance
	2.5.4	Maximum Pressure
	2.5.5	Explosion Energy
2.6	Toxic	Materials
	2.6.1	Limiting Long-Term Exposure
	2.6.2	Limiting Short-Term Exposure

	Contents

3	Exothe	rmic an	d Pressure-Generating Reactions	69	
	3.1	Formal	Kinetics Description of Chemical Reactions	69	
	3.2	Reactor	Models	70	
		3.2.1	Ideal Batch Reactor	71	
		3.2.2	Continuous Stirred Tank Reactor	80	
		3.2.3	Tubular Flow Reactor	82	
	3.3	Autocat	talytic Reactions	85	
	3.4	Polyme	rization	89	
	3.5	Extrem	e Process Conditions	9(
		3.5.1	High Pressures	90	
		3.5.2		91	
		3.5.3	High Temperatures	92	
		3.5.4	Low Temperatures	92	
	3.6	Endoth		96	
	Refere	nces		96	
4	Safe D	esign an	d Operation of Plants	97	
	4.1	Procedu	are for Ensuring Safety in Planning, Building		
		and Op	erating Plants	98	
		4.1.1		98	
		4.1.2	Planning, Construction and Commissioning		
			of Plants	98	
		4.1.3	Operation	00	
		4.1.4	Safety Management	00	
		4.1.5		0	
		4.1.6	Alarm and Hazard Defence Plans, Information		
			of the Public	01	
	4.2	Princip	les of Plant Safety and Fundamental Concepts 1	02	
		4.2.1	Inherent Safety Measures	07	
		4.2.2	Passive Safety Measures	13	
		4.2.3		14	
		4.2.4		17	
		4.2.5		18	
	4.3	Externa		37	
		4.3.1		38	
	4.4	Plant Layout and Spacing			
	4.5			4:	
		4.5.1		4	
		4.5.2	Protective Measures Against Fires	- 1	
				70	
	Refere	nces .	r	86	

Contents			хi

5.1 Safe Design and the Procurement of Safe Apparatuses and Work Equipment 190 5.2 Apparatuses, Machinery and Tools 191 5.3 Hazard Assessment 192 5.4 Personal Protective Equipment 197 5.5 Safe Handling of Chemical Substances 197 5.5.1 Filling, Draining and Conveying of Hazardous Materials 198 5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 6.0 Work with Special Hazards: Permit to Work System 205 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220	5	Perso	nal Safety and Personal Protective Equipment	189
5.2 Apparatuses, Machinery and Tools 191 5.3 Hazard Assessment 192 5.4 Personal Protective Equipment 197 5.5 Safe Handling of Chemical Substances 197 5.5.1 Filling, Draining and Conveying of Hazardous Materials 198 5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2 Programmable Electronic Systems 215 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 7.1 Safety Valves 2		5.1	Safe Design and the Procurement of Safe Apparatuses	
5.3 Hazard Assessment 192 5.4 Personal Protective Equipment 197 5.5 Safe Handling of Chemical Substances 197 5.5.1 Filling, Draining and Conveying of Hazardous Materials 198 5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2 Programmable Electronic Systems 215 6.2 1. Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 222 7.1				190
5.4 Personal Protective Equipment 197 5.5 Safe Handling of Chemical Substances 197 5.5.1 Filling, Draining and Conveying of Hazardous Materials 198 5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 7.1 Safety Valves 234 7.2 Bursting Disc Protection Device 234 7.3 Combination of		5.2	Apparatuses, Machinery and Tools	
5.5 Safe Handling of Chemical Substances 197 5.5.1 Filling, Draining and Conveying of Hazardous Materials 198 5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety		5.3	Hazard Assessment	192
5.5.1 Filling, Draining and Conveying of Hazardous Materials		5.4	Personal Protective Equipment	197
5.5.1 Filling, Draining and Conveying of Hazardous Materials		5.5	Safe Handling of Chemical Substances	197
5.5.2 Sampling 199 5.5.3 Cleaning of Vessels and Other Equipment 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for				
5.5.3 Cleaning of Vessels and Other Equipment. 200 5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4.1 Energy Balance fo			of Hazardous Materials	
5.6 Work with Special Hazards: Permit to Work System 202 References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4.1 Energy Balance for the Stationary Flow Process 234 <t< td=""><td></td><td></td><td>5.5.2 Sampling</td><td>199</td></t<>			5.5.2 Sampling	199
References 205 6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 235 7.4.4 Two-Phase Flow 245 7.4.5 Mass Flow Rate to Be			5.5.3 Cleaning of Vessels and Other Equipment	200
6 Safety of Process Plants by Process Control 207 6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.2 Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 235 7.4.4 Two-Phase Flow 247 7.4.5 Mass Flow Rate to Be Discharged 256 7.4.6 Relief		5.6	Work with Special Hazards: Permit to Work System	202
6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 242<		Refer	ences	205
6.1 Control System Characteristics and P&I Diagrams 208 6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 242<	6	Safet	v of Process Plants by Process Control	207
6.2 Programmable Electronic Systems 215 6.2.1 Components Close to the Process 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 235 7.4.4 Two-Phase Flow 242 7.4.5 Mass Flow Rate to Be Discharged 250	•			
6.2.1 Components Close to the Process. 217 6.3 Integration of PCE in the Safety Concept 218 6.3.1 Normal Operation. 219 6.3.2 Monitoring Malfunctions. 219 6.3.3 Damage Avoidance. 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements. 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 247 7.4.5 Mass Flow Rate to Be Discharged 256 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259				
6.3 Integration of PCE in the Safety Concept 6.3.1 Normal Operation		0.2		
6.3.1 Normal Operation 219 6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 243 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5.1 Deflagration and Detonation Arresters for Gases 255		63	-	
6.3.2 Monitoring Malfunctions 219 6.3.3 Damage Avoidance 219 6.3.4 Hazard Defence 220 6.3.5 General Requirements 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 247 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5.1 Deflagration and Detonation Arresters for Gases 259		0.2		
6.3.3 Damage Avoidance. 219 6.3.4 Hazard Defence. 220 6.3.5 General Requirements. 220 6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide. 223 References. 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves. 232 7.2 Bursting Disc Protection Device. 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device. 234 7.4 Dimensioning of Relief Devices. 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids. 236 7.4.3 Gases or Vapours. 235 7.4.4 Two-Phase Flow. 245 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems. 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259				
6.3.4 Hazard Defence				
6.3.5 General Requirements			•	
6.4 Case Study: Iron-Catalyzed Oxidation of Ethanol with Hydrogen Peroxide				
with Hydrogen Peroxide 223 References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 243 7.4.5 Mass Flow Rate to Be Discharged 256 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259		64		
References 228 7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 235 7.4.4 Two-Phase Flow 243 7.4.5 Mass Flow Rate to Be Discharged 256 7.4.6 Relief and Retention Systems 256 7.5.1 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259		0.4		223
7 Protection of Equipment (End-of-the-Pipe Technology) 231 7.1 Safety Valves 232 7.2 Bursting Disc Protection Device 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device 234 7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 236 7.4.4 Two-Phase Flow 247 7.4.5 Mass Flow Rate to Be Discharged 256 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259		Defer	, ,	
7.1 Safety Valves		Refer	checs	
7.2 Bursting Disc Protection Device. 234 7.3 Combination of Safety Valve and Bursting Disc Protection Device. 234 7.4 Dimensioning of Relief Devices. 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids. 236 7.4.3 Gases or Vapours. 239 7.4.4 Two-Phase Flow. 243 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems. 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259	7	Prote	ection of Equipment (End-of-the-Pipe Technology)	231
7.3 Combination of Safety Valve and Bursting Disc Protection Device		7.1	Safety Valves	232
7.3 Combination of Safety Valve and Bursting Disc Protection Device		7.2	Bursting Disc Protection Device	234
7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 239 7.4.4 Two-Phase Flow 241 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259		7.3		
7.4 Dimensioning of Relief Devices 234 7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 239 7.4.4 Two-Phase Flow 241 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259			Protection Device	234
7.4.1 Energy Balance for the Stationary Flow Process 234 7.4.2 Liquids 236 7.4.3 Gases or Vapours 239 7.4.4 Two-Phase Flow 243 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259		7.4		234
7.4.2 Liquids 236 7.4.3 Gases or Vapours 239 7.4.4 Two-Phase Flow 243 7.4.5 Mass Flow Rate to Be Discharged 250 7.4.6 Relief and Retention Systems 256 7.5 Constructive Measures of Explosion Protection 258 7.5.1 Deflagration and Detonation Arresters for Gases 259				234
7.4.3 Gases or Vapours				236
7.4.4 Two-Phase Flow				239
7.4.5 Mass Flow Rate to Be Discharged			•	
7.4.6 Relief and Retention Systems				
7.5 Constructive Measures of Explosion Protection				
7.5.1 Deflagration and Detonation Arresters for Gases 259		7.5		
			•	

xii Contents

		7.5.3	Safety Concept	266
	D - C	7.5.4	Flame Arresters for Dusts	267
	Keierei	ices		267
8	Risk			269
	8.1	Overvie	ew of Risk and Safety Analyses	269
	8.2	Risk Li	imits	275
		8.2.1	Individual Risk	278
		8.2.2	Collective Risk	278
	8.3	Represe	entation of Risks	279
	Refere			281
9	Investi	gation o	of Engineered Plant Systems	283
	9.1		nentals	283
		9.1.1	Failures and Safety Factors	285
		9.1.2	Input Information and Methods of Analysis	290
	9.2		natical Description of the Components	
			nnical Systems	326
		9.2.1	Exponential Distribution	330
		9.2.2	Other Distribution Types	331
		9.2.3	Constant Failure Probabilities	331
	9.3	Determ	ination of Reliability Data for Technical	
			nents	333
		9.3.1	Models	333
		9.3.2	Confidence Intervals	337
		9.3.3	Bayesian Evaluation of Reliability Data	339
		9.3.4	Treatment of Uncertainties	343
		9.3.5	Transferability of Reliability Data	344
	9.4		n Variables and Their Application	
			t Tree Analysis	345
		9.4.1	Series Configuration in the Sense of Reliability	347
		9.4.2	Parallel Configuration in the Sense of Reliability	348
		9.4.3	System with Negation	348
		9.4.4	Voting System of the Type 2-out-of-3	349
		9.4.5	The Multilinear Form of the Structure Function	
			and Determination of Reliability Parameters	
			for Systems	350
	9.5	Method	Is for Increasing the Survival Probability	550
			railability	356
		9.5.1	Systems with Reserve Elements	357
			Maintenance Models	361

<u>Contents</u> <u>xiii</u>

	9.6	Depend	ent Failures	378
		9.6.1	Causes	379
		9.6.2	Countermeasures	380
		9.6.3	Secondary Failures	382
		9.6.4	Functional Dependencies	383
		9.6.5	Common Cause Failures	384
		9.6.6	Closing Remark	386
	9.7	Human	Error	387
		9.7.1	Procedure for Analyzing Human Actions	390
		9.7.2	Important Factors of Influence	
			on Human Reliability	392
	9.8	Case St	tudies	406
		9.8.1	Fault Tree for the Trip System of a Plant	
			for Producing Nitroglycol	406
		9.8.2	CO ₂ Separation in a Rectisol Plant	410
		9.8.3	Fault Tree Analysis of the Nitrator	
			for the Production of Hexogen	414
		9.8.4	Comparison of the Availabilities	
			of Reactor Trip Systems	427
	Refere	nces		437
10	Conse	auences	of Accidents	441
	10.1		of Containment	445
		10.1.1	Frequencies of the Occurrence of a Loss	
			of Containment	445
		10.1.2	Leak Sizes	448
		10.1.3	Geometry of the Aperture	449
	10.2	Emissio	on from Leaks	449
		10.2.1	Discharge of Liquids from Vessels	451
		10.2.2	Discharge of a Liquid from a Pipe Leak	454
		10.2.3	Discharge of Gases or Vapours from Vessels	457
		10.2.4	Discharge of Gases and Vapours	
		10.2.4	from Pipe Leaks	460
		10.2.5	Discharge of a Two-Phase Mixture from Vessels	460
	10.3		ts	470
	10.5	10.3.1	Liquids	470
		10.3.1	Gases	473
		10.3.2	Two-Phase Flow and Flash Vaporization	476
	10.4		ormation and Pool Vaporization	482
	10.4		pheric Dispersion	489
	10.5	10.5.1	Airborne Dispersion	489
		10.5.1	•	501
			Dense Gas Dispersion	505
		10.5.3	Impact of Atmospheric Dispersion	202

	10.6	Fires and Explosions	511
		10.6.1 Pool Fires	511
		10.6.2 Gases	519
		10.6.3 Explosions	531
	10.7	BLEVE	550
	10.8	Dust Explosion	559
	10.9	Flight of Missiles	561
		10.9.1 Calculation of the Trajectory	561
		10.9.2 Determination of the Coefficients for the Equations	
		of the Flight Trajectory	564
	10.10		572
		10.10.1 Probability of Immediate Ignition	574
		10.10.2 Probability of Delayed Ignition	574
		10.10.3 Explosion	576
	10.11	Case Study: Risk Assessment for the Failure of a Natural	
		Gas High Pressure Pipeline	578
		10.11.1 Expected Frequencies of Occurrence, Release	
		Processes and Relevant Accident Consequences	579
		10.11.2 Accident Consequences	580
		10.11.3 Determination of the Expected Frequencies	
		for the Occurrence of the Scenarios	
		and Representation of the Risk	583
	Refere	ences	586
11			591
	Refere	ences	609
12		g of Appropriate Distances Between Industry	
		desidential Areas	611
	12.1		611
	12.2	Risk-Based Approach	612
		12.2.1 Initiating Events and Scenarios	613
		12.2.2 Characteristics and Exposure	616
		12.2.3 Consequences of Material Releases	616
		12.2.4 Damage and Risk	618
	12.3	Processing of Random Variables	619
	12.4	Risk Limits and Distances on the Basis	
		of Risk Considerations	619
		12.4.1 Risk Limits	619
		12.4.2 Distances	621
		12.4.3 Example for Land-Use Planning	621
	Refere	ences	623

Contents	χv
	

Appendix A:	GHS—Globally Harmonized System of Classification and Labelling of Chemicals	625
Appendix B:	Probit Relations, Reference and Limit Values	629
Appendix C:	Basics of Probability Calculations	637
Appendix D:	Coefficients for the TNO Multienergy Model and the BST Model	651
Index		655