Contents

1.	Hazardous properties of materials	1
1.1	Flammability	1
	Example 1.1: Empirical probabilities for fires and explosions	1
1.2	Explosion limits	2
	Example 1.2: Uncertainties of the explosion limits taking ethylene as an example	2
	Example 1.3: Determination of the lower and upper explosion limits of town gas	3
	Example 1.4: Determination of the minimum quantity of air for reducing a concentration of propane below the lower explosion limit	4
	Example 1.5: Avoiding an explosion while removing residual ethanol	5
1.3	Minimum ignition energy	8
	Example 1.6: Ignition of hydrogen or methane	9
	Example 1.7: Ignition of ethanol and benzene	10
	Example 1.8: Determination of most easily ignitable concentrations	11
1.4	Adiabatic flame temperature	12
	Example 1.9: Comparison of the adiabatic flame temperatures of hydrogen and methane	12
1.5	Explosions	13
	Example 1.10: Maximum pressure of a deflagration of methane	15
	Example 1.11: Maximum rates of pressure rise for deflagrations of propane and methane	15
	Example 1.12: Dust explosion	16
	Example 1.13: Assessment of the possibility of a transition from deflagration to detonation (DDT "Deflagration-Detonation-Transition")	18

1.6	Explosives	19
	Example 1.14: Characteristics of an anti-tank missile	21
	Example 1.15: Characteristics of a bomb	22
	Example 1.16: Generation of gaseous explosion products	24
1.7	Probit method	25
	Example 1.17: Calculation of probabilities of death and uncertainties	25
	Example 1.18: Effects of a release of hydrogen fluoride	26
	References for Chapter 1	28
2.	Exothermic and pressure-generating reactions	29
2.1	Adiabatic temperature rise	29
	Example 2.1: Adiabatic temperature rise in a chemical reactor	29
	Example 2.2: Final temperature of an adiabatic temperature rise	30
2.2	Transient behaviour and runaway of reactions	30
	Example 2.3: Determination of the reaction time of a second-order reaction	30
	Example 2.4: Time-dependence of the temperature of a reaction after cooling failure	32
	Example 2.5: Partial failure of reactor cooling and the Semenov Diagram	35
	Example 2.6: Time for reaching the maximum rate of reaction $(TMR_{ad}: Time to Maximum Rate under Adiabatic Conditions)$	40
2.3	Autocatalytic reaction	42
	Example 2.7: Time-dependence of an autocatalytic reaction	42
	References for Chapter 2	48

х

3.	Safe design and operation of industrial plants	49
3.1	Inherent safety	49
	Example 3.1: Reduction of the process inventory in producing nitroglycol	49
	Example 3.2: Substitution of hydrogen cyanide in the production of Acrylonitrile	50
	Example 3.3: Reduction of the mass of reacting material by dilution	51
3.2	Strength of materials	53
	Example 3.4: Probabilistic interpretation of the safety factor	53
	Example 3.5: Categorization of a buffer tank according to the	
	guideline 2014/68/EU	56
3.3	Safe operation	58
	Example 3.6: Determination of the time available for an emergency discharge of a reactor	58
	Example 3.7: Careful start of industrial equipment	60
	Example 3.8: Thermal shock loading of a feedwater pipe	62
	Example 3.9: Water hammer	66
	Example 3.10: Leakage from a storage tank for bitumen	70
3.4	Self-heating and self-ignition	75
	Example 3.11: Self-heating of a bulk of material	75
3.5	Static electricity as ignition source	77
	Example 3.12: Determination of the breakdown voltage and permissible voltage	78
	Example 3.13: Energy released by an electrical discharge	78
	Example 3.14: Ignition of petrol spilled while filling the tank of a car	79

3.6	Electrostatic charging	80
	Example 3.15: Calculation of the time-dependence of the electrical charge in a container filled with toluene	82
	Example 3.16: Reduction of the ignition hazard by reducing the Filling velocity while filling the container	85
	Example 3.17: Filling of a barrel with a bulk material	86
	References for Chapter 3	87
4.	Occupational safety	89
	Example 4.1: Fall from a scaffold	89
	Example 4.2: Injury from electrical shock	91
	Example 4.3: Fall down the stairs	92
	Example 4.4: Repair of a biogas plant	93
	Example 4.5: Dispersion of hydrogen fluoride (HF) after release	95
	References for Chapter 4	97
5.	Process control	99
	Example 5.1: Control characteristics of a P and a PI controller	99
	References for Chapter 5	106
6.	Protection of equipment	107
6.1	Dimensioning of relief equipment	107
	Example 6.1: Dimensioning a safety valve and a bursting disc for the pressure relief of a liquid	115
	Example 6.2: Dimensioning of a safety valve for the pressure relief of a gas (critical discharge)	117
	Example 6.3: Dimensioning of a safety valve for the pressure relief of a gas (subcritical discharge)	118
	Example 6.4: Dimensioning of a safety valve for pressure relief with two-phase flow – critical (choked) discharge	119

	Example 6.5: Dimensioning of a safety valve for pressure relief with two-phase flow – subcritical (unchoked) discharge	120
	Example 6.6: Dimensioning of a safety valve for pressure relief with two-phase flow – subcooled liquid	121
	Example 6.7: Dimensioning of a safety valve for pressure relief with two-phase flow – water and air	122
	Example 6.8: Incorrect dimensioning of a safety valve	123
6.2	Pressure changes in containments	124
	Example 6.9: Pressure relief of a gas-filled tank in case of fire	124
	Example 6.10: Pressure changes inside a vessel following temperature changes	127
	Example 6.11: Pressure rise in a trapped liquid volume due to temperature increase	128
	References for Chapter 6	132
7.	Event Tree Analysis	133
	Example 7.1: Event tree analysis for the release of a liquefied gas	133
	Example 7.2: Event tree for a runaway of an exothermic reaction	135
	Example 7.3: Development of a probabilistic treatment of an event tree	135
	Example 7.4: Scenarios for a firefighting operation in a residential house fire	143
	References for Chapter 7	145
8.	Fault Tree and Markov Analyses	147
	Example 8.1: Fault tree for a system for cooling a reactor for an exothermic reaction	147
	Example 8.2: Determination of the failure rate of gas storage tanks	150
	Example 8.3 Failure rate of multi-port valves	151
	Example 8.4 Periodic proof-testing	152

	Example 8.6: Probability of failure on demand of an emergency trip system with an inhibitor	160
	Example 8.7 Fault tree for the trip system of a plant for producing	
	nitroglycol	162
	Example 8.8: CO ₂ separation in a Rectisol plant	167
	Example 8.9: Availability of a power plant	171
	References for Chapter 8	178
9.	Consequences of Accidents	179
	Example 9.1: Determination of leak sizes	179
9.1	Discharge processes	182
9.1.1	Liquids	182
	Example 9.2: Discharge of petrol from a cylindrical vessel	182
	Example 9.3: Discharge of petrol from a spherical vessel	185
	Example 9.4: Discharge from a pipe leak	188
	Example 9.5: Leak from a naphtha pipe	192
9.1.2	Gases	193
	Example 9.6: Discharge of ethylene from a vessel	193
	Example 9.7 Discharge of isobutylene from a vessel	195
9.1.3	Two-phase mixtures	197
	Example 9.8: Determination of the vapour quality of pressure liquefied propylene	200
	Example 9.9: Determination of the average and local volume fractions of vapour	203

9.2	Free jets	206
9.2.1	Liquids	207
	Example 9.10: Free jet from a vessel leak	207

9.2.2	Gases	210
	Example 9.11: Vertically upright free jet of ethylene from a vessel leak	210
9.3	Flash vaporization and two-phase flow	214
	Example 9.12 Flash vaporization of propane	216
	Example 9.13: Horizontal free jet according to Fauske's model	216
9.4	Pool formation and evaporation or vaporization from the pool	221
	Example 9.14: Vaporization of a spill of petrol	224
	Example 9.15: Release of hydrochloric acid during transfer of HCl to a storage tank	225
	Example 9.16: Release of hydrogen fluoride into a water trap	227
	Example 9.17: Release and vaporization of phenyl isocyanate	229
	Example 9.18: Evaporation of a pool of chlorine from a refrigerated storage	232
9.5	Atmospheric dispersion	235
9.5.1	Modelling	236
	Example 9.19: Steady-state emission of nitrogen	241
9.5.2	Impacts of atmospheric dispersion	242
	Example 9.20: Effects of a puff release of carbon monoxide	242
	Example 9.21: Flammable fraction of a methane cloud	243
	Example 9.22: Health impact of chlorine exposure	245
9.6	Fires and explosions	246
9.6.1	Pool fires	246
	Example 9.23: Fire in a petrol filling station	251
9.6.2	Gases	255
	Example 9.24: Fireball after a release of propane	256
9.6.3	Jet flames	258
	Example 9.25: Jet flame of ethylene	258

9.6.4	Explosions	260
	Example 9.26: Effects of an explosion of hexogen	264
	Example 9.27: Comparison of two processes for producing nitroglycol (reduction of inventory)	265
	Example 9.28: Explosion effects of a cloud of propane	267
9.7	BLEVE	268
	Example 9.29: BLEVE on release of pressure liquefied propane	270
9.8	Dust explosion	275
	Example 9.30: Dust explosion	275
9.9	Missile flight	277
	Example 9.31: Missile flight after vessel rupture	281
	References for Chanter 9	286
		200
10.	Functional safety	289
	Example 10.1: Target values for the unavailabilities of safety-related	
	systems	290
	Example 10.2: Determination of SIL classes for the safety related	201
	system of a storage tank for petrol	291
	Deferences for Chapter 10	207
	References for Chapter fo	291
11.	Appropriate safety distances	299
	Example 11.1: Planning of a plant on a virgin terrain (distance	
	determination without knowledge of details)	299
	Example 11.2: Determination of the appropriate safety distance	
	based on a pool fire of petrol	300
	Example 11.3: Release of ammonia in supercritical state	202
	and subsequent aunospheric dispersion	303

Example 11.4: Appropriate safety distances of plants within an existing establishment (determination with knowledge of details)	305
Example 11.5: Appropriate safety distances for a release of propane on terrains with different properties	315
Example 11.6: Appropriate safety distance for a planned storage tank for pressure liquefied propane	317
Example 11.7: Release of hydrogen fluoride in an industrial hall	318
Example 11.8: Release of hydrofluoric acid from a container (IBC)	321
Example 11.9: Average and position-dependent concentration of HF in an industrial hall after a release of hydrofluoric acid	325
Example 11.10: Release of Diesel fuel and subsequent pool fire	328
Example 11.11: Small fire of a herbicide	331

References for Chapter 11

333