

## Contents

Preface XI

<b>1</b>	<b>Introduction</b>	<b>1</b>
	<i>Ulrich Krause</i>	
1.1	Problem Description	1
1.2	Influence of Material Properties on Fire	3
1.2.1	Particle Size Distribution, Particle Shape and Internal Surface Area	3
1.2.2	Bulk Porosity and Bulk Density	6
1.2.3	Porosity of Individual Particles	7
1.2.4	Particle Density	8
1.2.5	Humidity	8
1.3	Chemical Properties of Bulk Goods	9
1.3.1	Chemical Structure	9
1.3.2	Heat of Formation and Calorific Value	10
	References	11
<b>2</b>	<b>Ignition Sources</b>	<b>13</b>
	<i>Vytenis Babrauskas and Ulrich Krause</i>	
2.1	Introduction	13
2.2	External Ignition Sources	13
2.2.1	Hot Solids, Liquids or Gases	14
2.2.1.1	Ignition of Gases by Hot Solids	14
2.2.1.2	Ignition of Dust Clouds by Hot Solids	15
2.2.1.3	Ignition of Solids by Hot Solids	18
2.2.2	Flames or Remote Burning Objects	18
2.2.3	Electric Current, Static Electricity, Electromagnetic Waves and Particulate Radiation	19
2.2.3.1	Electric Current	20
2.2.3.2	Static Electricity	21
2.3	Self-Heating	23

2.4	Physical Characteristics of Self-Ignition Processes and Smoldering Fire Propagation 27 <i>Ulrich Krause</i> References 29
<b>3</b>	<b>Fire Risk Assessment 33</b> <i>Javier García Torrent and Enrique Querol</i>
3.1	Introduction 33
3.2	Experimental Techniques 34
3.2.1	Ignition Sensitivity 34
3.2.1.1	Minimum Ignition Temperature (MIT) 34
3.2.1.2	Minimum Explosible Concentration (Lower Explosion Limit (MEC/LEL)) 37
3.2.1.3	Minimum Ignition Energy (MIE) 37
3.2.2	Explosion Severity 37
3.2.2.1	Explosion Pressure ( $P_{\max}$ ) 37
3.2.2.2	Maximum Rate of Pressure Rise ( $dp/dt$ ) 38
3.2.2.3	$K_{\max}$ Specific Constant 38
3.2.3	Thermal Susceptibility 38
3.2.3.1	Maciejasz Index (MI) 39
3.2.3.2	Temperature of Emission of Flammable Volatiles (TEV) 39
3.2.3.3	Thermogravimetry (TG) Test 39
3.2.3.4	Differential Scanning Calorimetry (DSC) 40
3.2.3.5	Susceptibility Evaluation: Activation Energy ( $E_a$ ) 41
3.2.3.6	Susceptibility Evaluation: Characteristic Oxidation Temperature ( $T_{\text{charac}}$ ) 43
3.2.4	Thermal Stability 43
3.2.4.1	Self-Ignition Temperature (SIT) 44
3.2.5	Classification of Solid Dangerous Goods 45
3.2.5.1	Solids which are Readily Combustible 47
3.2.5.2	Substances Liable to Spontaneous Combustion 47
3.2.5.3	Substances which, in Contact with Water, Release Flammable Gases 47
3.2.5.4	Oxidizing Substances 47
3.2.6	Other Tests 48
3.2.6.1	Flammability 48
3.2.6.2	Burning Behavior 48
3.2.6.3	Greuer Oven 48
3.2.6.4	Impact Sensitivity 48
3.2.6.5	Friction Sensitivity 49 References 49
<b>4</b>	<b>Explosion Risk and Protection 51</b> <i>Kazimierz Lebecki</i>
4.1	Essential Conditions for Explosion Occurrence 51
4.2	Parameters of Dust Explosion; Definitions 51

4.3	Some Physical and Chemical Properties of Agricultural Dusts	53
4.4	Explosion Characteristics	55
4.5	Propagation of Explosion	59
4.6	Dynamics of Explosions in Long Ducts and Galleries	62
4.7	Causes of Fires and Fire–Explosion Protection	65
4.7.1	Age of the Facilities, Maintenance and Repair Work	65
4.7.2	Nature of Processed Materials	65
4.7.3	Ignition Sources	65
4.7.4	Plant Operation	66
4.7.5	Type of Buildings and Facilities	66
4.7.6	Equipment for Dust Collection	66
4.7.7	Plant Automation	66
4.7.8	Human Factor	67
4.8	Fire and Explosion Prevention and Protection in the Storage of Agro, Feed and Food Products	67
4.9	Explosions	67
4.9.1	Prevention	67
4.9.1.1	Limitation of Dust Emission	68
4.9.1.2	Limitation of Ignition Sources	68
4.9.1.3	Reduction of Oxygen Content	69
4.9.2	Protection	70
4.9.2.1	Pressure-Resistant Buildings and Equipment	70
4.9.2.2	Reduction of the Maximum Explosion Pressure (Venting)	71
4.9.2.3	Explosion Suppression by Flame Extinguishing	71
4.9.2.4	Isolating the Various Installations (Isolating Devices)	72
4.9.2.5	Operation of Protective System	72
4.10	Fire	73
4.10.1	Prevention	73
4.10.1.1	Combustible Elements	73
4.10.1.2	Ignition Sources	74
4.10.2	Protection	75
	Further Reading	77
<b>5</b>	<b>Fire Detection</b>	<b>79</b>
	<i>Ralf Schäckel and translated by Ulrich Krause</i>	
5.1	Introduction	79
5.2	Smoke Detectors	80
5.2.1	General	80
5.2.2	Optical Smoke Detectors	80
5.2.3	Ionization Smoke Detectors	81
5.2.4	Fire Gas Detectors	81
5.3	Flame Detectors	81
5.4	Spark Detectors	83
5.4.1	Daylight-Sensitive Spark Detectors	85
5.4.2	Daylight-Insensitive Spark Detectors	85

5.5	Heat Detectors	85
5.6	Application Examples	87
5.6.1	Fire Protection Silo in a Fiber Board Factory	87
5.6.2	Recycling of Metal Parts, for example Car Residues	89
5.6.3	Feeding Line of a Silo Plant with 24 Silo Cells	90
5.6.4	Silo of a Biomass Power Station	91
	References	92
<b>6</b>	<b>Case Studies</b>	<b>93</b>
	<i>David Westermann and Rolf Eckhoff</i>	
6.1	Fire in a Silo for Wood Pellets in Esbjerg, Denmark, 1998–1999	93
	<i>David Westermann</i>	
6.1.1	Summary	93
6.1.2	Background	94
6.1.2.1	Siting of the Silo	94
6.1.2.2	Fire and Rescue Services in Esbjerg	94
6.1.2.3	The Silo Building	94
6.1.2.4	Construction	94
6.1.2.5	Emptying and Filling	94
6.1.2.6	Instrumentation	95
6.1.2.7	Explosion Venting	95
6.1.2.8	Description of Contents	95
6.1.2.9	Wood Pellets	96
6.1.3	Normal Extinguishing Practice	96
6.1.3.1	Fires in Grain and Animal Food Silos	96
6.1.3.2	Fires in Wood-Containing Silos	96
6.1.4	Incident Chronology	97
6.1.4.1	Day 1 – Initial Confusion	97
6.1.4.2	Day 2 – Initial Problems	98
6.1.4.3	Day 3 (Saturday) – Further Problems	98
6.1.4.4	Day 4 – Further Precautions	98
6.1.4.5	Day 5 – Further Problems	99
6.1.4.6	Day 6	100
6.1.4.7	Day 7	101
6.1.4.8	Day 8	101
6.1.4.9	Day 9	101
6.1.4.10	Day 10	101
6.1.4.11	Day 11	102
6.1.4.12	Day 12	102
6.1.4.13	Day 13	102
6.1.4.14	Day 14	102
6.1.4.15	Day 15	102
6.1.4.16	Day 16	102
6.1.4.17	Day 17	103
6.1.4.18	Day 18	103

6.1.4.19	Day 19	103
6.1.4.20	Day 20	103
6.1.4.21	Day 21	104
6.1.4.22	Day 22	104
6.1.4.23	Day 23	104
6.1.4.24	Day 24	104
6.1.4.25	Day 25	104
6.1.4.26	Day 26	105
6.1.4.27	Day 27	105
6.1.4.28	Day 28	105
6.1.4.29	Day 29	105
6.1.4.30	Day 30	105
6.1.5	Problems Arising	107
6.1.5.1	Unexpected Explosions	107
6.1.5.2	Fire Spread from Cell to Cell	107
6.1.5.3	Compacting of Silo Contents	107
6.1.5.4	Difficulties with Emptying Cells	107
6.1.5.5	Breakdown of Ancillary Services	108
6.1.5.6	Measurements	108
6.1.5.7	Weather	108
6.1.5.8	Access Lofts	109
6.1.5.9	Personnel	109
6.1.6	Costs and Material Usage	110
6.2	Further Case Studies	110
	<i>Rolf K. Eckhoff</i>	
6.2.1	Smoldering Gas Explosion in a Large Storage Facility for Grain and Feedstuffs in Tomylovo in the Kuibyshev Region of USSR	110
6.2.2	Smoldering Gas Explosion and Subsequent Successful Extinction of Smoldering Combustion in Pelletized Wheat Bran in a Silo Cell at Nord Mills, Malmö, Sweden, in 1989	112
6.2.3	Extinction Using Water of Smoldering Fire in a Fish Meal Silo in Norway in 1992	114
	References	115
<b>7</b>	<b>Fighting Silo Fires</b>	<b>117</b>
	<i>Ulrich Hoischen, Jörg Kayser, and translated by Ulrich Krause</i>	
7.1	Introduction	117
7.2	Inert Gases for Silo Fire Fighting	119
7.3	Nitrogen	120
7.4	Carbon dioxide	120
7.5	Fighting a Silo Fire in an Animal Food Production Plant	121
7.5.1	Description of the Situation	121
7.5.2	State Before the Fire	121
7.5.3	Outbreak of the Fire	121
7.5.4	Fire Fighting	122

7.5.5	Emptying the Silo Cell	123
7.5.6	Summary and Conclusion	124
7.6	Test Inertization of a Malt Silo	124
7.6.1	Description of Situation	124
7.6.2	Estimating the Necessary Amount of Inert Gas	125
	References	125
<b>8</b>	<b>Necessary Fire Prevention Measures for Silos with Flammable Solid Bulk Materials in Connection with Inerting During a Fire</b>	<b>127</b>
	<i>Ulrich Hoischen, Jörg Kayser, and translated by Ulrich Krause</i>	
8.1	Inerting of Silos with Flammable Solid Bulk Materials in Case of Fire	127
8.2	Recommendations for Construction, Processing and Operation	128
8.2.1	Construction	128
8.2.2	Measures During Processing and for Fire Detection	129
8.2.3	Operational Measures	129
8.3	Measures in Case of Fire	131
8.3.1	Alerting	131
8.3.2	General Measures	131
8.3.3	Sealing of the Silo	132
8.3.4	Inerting and Concentration Measurements	132
8.3.5	Emptying the Silo	132
8.4	Summary	133
<b>9</b>	<b>Predictive Tools for Hazard Assessment of Self-Ignition</b>	<b>135</b>
	<i>Ulrich Krause</i>	
	References	138
	<b>Index</b>	<b>139</b>