# Contents

Acknowledgment XI Preface XIII

## 1 Classification of Explosives 1

- 1.1 Initiation Sensitivity 1
- 1.2 Size 1
- 1.3 Usage 2
- 1.4 Physical Form 2

### 2 Explosive Science 5

- 2.1 Introduction 5
- 2.1.1 Low Explosives 5
- 2.1.2 High Explosives 5
- 2.2 Initiation and Detonation 6
- 2.2.1 Mechanism 6
- 2.3 Propagation and Detonation 7
- 2.3.1 Propagation 7
- 2.3.2 Detonation 8
- 2.3.2.1 Ideal/Nonideal Detonation/Critical Diameter/Ideal Diameter 9

v

- 2.3.2.2 Detonation Pressure and Velocity 9
- 2.4 Reaction Chemistry in Explosives 11
- 2.4.1 Heat of Reaction 11
- 2.4.2 Rules of Hierarchy 12
- 2.4.3 Calculation of Oxygen Balance and Fuel Values 12 References 13

## **3** Ammonium Nitrate Explosives 15

- 3.1 Introduction 15
- 3.1.1 Chronology 15
- 3.2 Design of Commercial Explosives 16
- 3.2.1 Importance of Oxygen Balance 16
- 3.2.2 Physical, Performance, and Safety Requirements 17

VI Contents

3.3	Tests 17
3.3.1	Ballistic Mortar Test 18
3.3.2	Trauzl Lead Block Test 19
3.3.3	Velocity of Detonation (VOD) 20
3.3.4	Gap Test and Continuity of Detonation Test 22
3.3.5	Aquarium Test 23
3.3.6	Double Pipe Test 23
3.3.7	Cylinder Test (Crushing Strength) 24
3.3.8	Plate Dent Test 24
3.3.9	Underwater Test (UWT) 24
3.3.10	Crater Test 26
3.4	Assessment of Safety and Stability Characteristics 27
3.4.1	Impact Test 27
3.4.2	Torpedo Friction Test 27
3.4.3	Accelerated Hot Storage (ageing Test) 27
3.4.4	Cold Temperature Storage Test 28
3.4.5	Thermal Stability Tests Using DTA and TGA Procedures 28
3.5	Summary 29
	References 29
4	Ammonium Nitrate and AN/FO 31
4.1	Introduction and History 31
4.2	Physical and Chemical Properties of Ammonium Nitrate 32
4.2.1	Basic Data 32
4.2.2	Decomposition Chemistry of AN 32
4.2.3	Phase Transition in AN and its Importance in Explosives 33
4.3	Manufacture of Ammonium Nitrate 35
4.3.1	Prilled Ammonium Nitrate 36
4.4	Ammonium Nitrate Fuel Oil Explosives 39
4.4.1	Background 39
4.4.2	AN/FO Manufacture 39
4.4.2.1	Mixing Process and Equipment 39
4.4.2.2	Continuous Process 40
4.4.2.3	Bulk Delivery Systems 40
4.4.3	Properties of AN/FO 41
4.4.3.1	Physical 41
4.4.3.2	Oil Absorbency and Porosity/Bulk Density/Crushing Strength 41
4.4.3.3	Resistance to Effect of Temperature Cycling 44
4.4.4	Characteristics of ANFO 45
4.4.4.1	Density/Strength 45
4.4.4.2	Strength of the AN/FO Explosive 46
4.4.4.3	Energy Content of AN/FO 46
4.4.4.4	Velocity of Detonation and Effective Priming 47
4.4.4.5	Mechanism of Detonation Propagation in AN/FO 49
4.4.4.6	Influence of Fuel 50

Contents VII

- 4.4.4.7 Effect of Moisture/Wet Boreholes/Water-Resistant AN/FO 50
- 4.4.4.8 Water-Resistant AN/FO 52
- 4.4.4.9 Increasing the Energy of AN/FO and its Fume Characteristics 52
- 445 Safety Considerations in AN/FO 55
- 4.4.6 Summary – AN/FO Explosives 56
- 4.4.7 Quality Checks 56 References 58 Further Reading 58

#### Slurries and Water Gels 59 5

- 5.1 Development 59
- 5.2 Design 59
- 5.2.1 Large-Diameter Packaged Product (Water Gels) 60
- 5.2.2 List of Ingredients 60
- 5.2.3 Small-Diameter, Cap-Sensitive Water Gels 60
- 5.2.4 Bulk Delivery Product 61
- 5.2.5 Basic Concepts of Formulation 61
- 5.2.5.1 Oxygen Balance 61
- 5.2.5.2 Thumb Rules for Design 62
- 5.2.5.3 Role of Water 63
- 5.2.5.4 Basic Composition and Process 65
- 5.3 Process Technology 66
- Batch Process 5.3.1 66
- 5.3.2 Continuous Process 68
- 5.3.3 68 Packaging Systems
- 5.4 Quality Checks 71
- Raw Materials 71 5.4.1
- End Product Specification 73 5.4.2
- 5.4.2.1 Development of New Formulations 73
- Role of Aluminum in Water Gels and Slurry Explosives 5.4.3 74
- 5.4.3.1 Atomized and Flake Powders 74
- 5.4.3.2 Aluminum Water Reaction 78
- 5.4.3.3 Important Tests for AL Powder for Use in AN-Based Water Gel Explosives 80
- 5.4.4 In-Process and Finished Product Checks 84
- 5.4.4.1 Oxidizer Blend Composition 84
- 5.4.4.2 Solid Ingredients 85
- 5.4.4.3 Liquid Ingredients 85
- 5.4.4.4 Mixing 85
- 5.4.4.5 Packing 86
- Performance Tests 86 5.4.5
- 5.4.6 Safety Tests 87
- Gap Test/COD 87 5.4.6.1
- 5.4.6.2 COD 87
- 5.4.7 Storage Tests 87

VIII Contents

5.4.8	Gel Condition Evaluation 89	
5.4.9	Waterproofness Test 90	
5.4.10	Effect of (Hydrostatic) Pressure 90	
5.5		91
5.5.1	Slippery Floor 92	
5.5.2	Health Hazard 92	
5.6	Role of GG 92	
5.6.1	Application in Water Gels and Slurries 93	
5.6.2	Specification of Typical GG Used in Water Gels 94	
5.6.3	Cross-Linking 95	
5.6.4	Mechanism of Hydration 96	
5.7	Permissible Explosives 98	
5.7.1	Design Criteria 98	
5.7.2	Tests for Permissibility 99	
5.7.3	Other Tests requirement 100	
5.7.3.1	Deflagration Tests 100	
5.7.4	Behavior of Water Gels in Permissibility Tests 101	
5.7.5	Toxic Fumes and Typical Formulation 104	
5.7.6	Strength of Permissible Water Gels 104	
5.8	General Purpose Small-Diameter Explosives (GPSD) 105	
5.8.1	Design Criteria and Composition 105	
5.9	Sensitizers 106	
5.9.1	Inorganic 106	
5.9.2	Organic Sensitizers 107	
5.9.3	Air/Gas/Synthetic Bubble Sensitizers 108	
	References 111	
	Further Reading 112	
6	Emulsion Explosives 113	
6.1	Introduction 113	
6.2	Concept of Emulsion Explosives 113	
6.3	General Composition of Emulsion Explosives 114	
6.4	Structure and Rheology 115	
6.5	Composition and Theory of Emulsion Explosives 117	
6.6	Manufacture 118	
6.6.1	Types of Emulsion Explosive Products 118	
6.6.2	Manufacturing Process 118	
6.6.2.1	Batch Process 119	
6.6.2.2	Semicontinuous Operation 119	
6.6.2.3	Fully Continuous Process 120	
6.6.2.4	Critical Equipment for Production of Emulsion	
	Explosives 121	
6.6.2.5	Pumps 122	
6.6.2.6	Packaging Equipment for Emulsion Explosives 122	
6.6.3	Raw Material for Emulsion 123	

- 6.6.3.1 Fuel Blends 123
- 6.6.4 Sensitizing in Emulsion Explosives 125
- 6.6.4.1 Air Entrapment or Occlusion while Emulsification by Mechanical Agitation 125
- 6.6.4.2 Chemical Gassing 125
- 6.6.4.3 Hollow Particles 126
- 6.6.5 Crystal Habit Modifiers 127
- 6.6.6 Emulsion Promoters 128
- 6.6.7 Emulsion Stabilizers 128
- 6.6.8 Emulsion Chemistry and Understanding Emulsifiers: Key to Good Emulsions 129
- 6.6.9 Concept of HLB and Its Use in Emulsification 133
- 6.6.9.1 Effect of Factors on Stability of Emulsions 135
- 6.6.10 Polymer Systems in Emulsion Explosives 138
- 6.7 Quality Checks 139
- 6.7.1 Raw Materials 139
- 6.7.2 Process Audit 140
- 6.7.3 Special Tests for Emulsions 141
- 6.8 Explosive Properties of Emulsion Matrix/Explosives 142
- 6.8.1 Channel Effect 144
- 6.9 Permissible Emulsions 145
- 6.10 General Purpose Small-Diameter (GPSD) Emulsion Explosives 147
- 6.11 Bulk Emulsions 149
- 6.12 Heavy AN/FO 151
- 6.13 Packaged Large-Diameter Emulsion Explosives 153 References 154 Further Reading 155

### 7 Research and Development 157

- 7.1 Areas of Interest 158
- 7.2 Development Work and Upscaling 159
- 7.3 Management of R&D 161

# 8 Functional Safety during Manufacture of AN Explosives 163

- 8.1 Introduction Personal View Point on Safety 163
- 8.2 Safety Considerations in AN Explosives 165
- 8.2.1 In AN/FO 165
- 8.2.2 In Slurries and Emulsions 166
- 8.2.3 Electrostatic Ignition 167
- 8.2.4 Lightning Protection 168
- 8.2.5 Runaway Reactions 168
- 8.2.6 Venting as Means of Protection 170
- 8.2.7 Explosion Suppression Technology 171
- 8.3 Explosion Hazards in Equipment 172
- 8.3.1 Hazards Associated with Pumping of Explosives 172

**X** Contents

8.3.2	Possible Hazards during Packing 175
8.4	Concluding Remarks 176
	References 177
9	Economics of AN-Based Explosives 179
9.1	In Manufacture 179
9.2	In Applications 181
9.2.1	Condition of Explosive 182
9.2.2	Coupling and Priming 183
9.2.3	Stemming and Confinement 184
9.2.4	Explosives–Rock Interaction 185
9.2.5	Explosives Energy Optimization in Blasting 185
9.3	Blast Design 186
9.4	Influence of Explosives in Underground Mining 190
	References 193
10	References 193 Current Status and Concluding Remarks 195
10	Current Status and Concluding Remarks 195
10	
10	Current Status and Concluding Remarks 195 Appendix A 199
	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident
B.1	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203
B.1 B.2	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203 Detailed Inspection 204
B.1 B.2 B.3	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203 Detailed Inspection 204 Interviewing and Questioning 205
B.1 B.2 B.3 B.4	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203 Detailed Inspection 204 Interviewing and Questioning 205 Collection of Samples 205
B.1 B.2 B.3 B.4 B.5	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203 Detailed Inspection 204 Interviewing and Questioning 205 Collection of Samples 205 Examination of Witnesses 206
B.1 B.2 B.3 B.4	Current Status and Concluding Remarks 195 Appendix A 199 Appendix B: Guidelines for Investigation of an Accident Introduction 203 Detailed Inspection 204 Interviewing and Questioning 205 Collection of Samples 205

203

Index 209