Contents

Foreword xi

Acronyms xiii

Preface xv

Chapter 1 Industrial Accidents Involving Large Vapor/Steam Explosions 1

1.1 Non-Nuclear Explosion Boiling Studies 1
1.1.1 Smelt–Water Explosions 2
1.1.2 Metal–Water Interactions 2
1.1.3 Intentional LNG Spills 3
1.2 Nuclear Incidents 4
1.2.1 Nuclear Test Reactors 4
1.2.2 Water-Cooled versus Water-Moderated Thermal Reactors 7
1.3 Objective of This Book 8

Chapter 2 Basic Considerations of Large-Scale Vapor Explosions and Their Application to Nuclear Fast and Thermal Reactor Safety 11

2.1 Technical Basis for Coarse Intermixing, Triggering, and Propagation 11
2.1.1 Coarse Intermixing 20
2.1.2 Triggering an Explosion 22
2.1.3 Propagation of an Explosion and Fine-Scale Fragmentation 24
2.2 Large-Scale Vapor Explosion Requirements 28
2.3 Application to Nuclear Reactor Systems 34
2.4 Assessment of Fuel–Coolant Interactions in the Fast Breeder Reactor Core Disruptive Accident 38
2.4.1 Introduction 38
2.4.2 General Behavior Principles and Contact Modes 39
2.4.3 CORECT-II Experiments 49
2.4.4 Concluding Remarks and Summary 54

Chapter 3 Experimental Basis for Water-Cooled Reactor Evaluations 57

3.1 Methodology for Assessing the Coarse Mixing Conversion Ratios for Explosive Interactions 59
3.2 Early Investigations with Reactive Metals 65
3.2.1 Long's Aluminum–Water Studies 67
3.2.2 Aluminum–Water Studies by Hess 69
3.2.3 Reactive Metal–Water Studies by Higgins 70
3.2.4 Shock Tube Tests by Wright 75
3.3 Sandia National Laboratory Experiments 77
3.3.1 Early Sandia Thermite and Corium Experiments 77
3.3.2 Sandia Steam Explosion Efficiency Studies and FITS-A Tests 80
3.3.3 Sandia FITS-B Tests 88
3.3.4 Single-Droplet Tests 93
3.4 Winfrith Tests 100
3.4.1 Aluminum–Water Experiments 100
3.4.2 Experimental Scaling of Melt–Water Interactions 101
3.4.3 Stratified Aluminum–Water Tests 105
3.4.4 Prototypic Molten Fuel–Water Tests 105
3.5 JAERI Steam Explosion Tests 109
3.6 ISPRA KROTOS Experiments 113
3.7 The FARO Tests 118
3.8 The COTELS Investigations 122
3.9 The TROI Experiments 127
3.10 Argonne National Laboratory Experiments 130
3.10.1 FCI Experiments with Realistic Core Materials 130
3.10.2 Aluminum–Water Experiments 131
3.10.3 ZREX Test Series 132
3.11 Experiments Demonstrating the Influence of System Pressure 142
3.11.1 ANL Freon-22 and Mineral Oil Experiments 144
3.11.2 The ISPRA Salt–Water Experiments 149
3.11.3 The JAERI ALPHA Tests 154
3.11.4 Related Small Quantity Experiments 154
3.11.4.1 Nelson's Experiments on the Influence of Pressure 154
3.11.4.2 Experiments Reported by Avedisian 155
3.11.4.3 Experiments Reported by Frost and Sturtevant (1986) 156
3.11.4.4 Water–Oil Emulsion Experiments Reported by Cho et al. (1991) 157
3.12 Influence of Stratified Conditions on the Reactor Vessel or on the Containment Floor 159
3.12.1 Investigations of Steam Explosion Interactions in a Stratified Configuration 159

3.12.1.1 The Investigations of Fry and Robinson (1979) 159
3.12.1.2 Experiments Reported by Anderson et al. (1988) 161
3.12.1.3 Experiments Performed by Bang and Corradini (1991) 165
3.12.1.4 Experiments Performed by Frost et al. (1993 and 1995) 170
3.12.1.5 Experiments Performed by Sainson et al. (1993) 173
3.12.1.6 Experiments Performed at the Swedish Royal Institute 174
3.12.1.7 Stratified Experiments with Gas Injection 179
3.12.2 Evaluation of Stratified Conditions 179
3.13 Annular Flow Configuration: FARO Test L-33 181
3.14 Influence of Forced Interaction Conditions 186
3.14.1 The Molten Fuel Moderator Interaction Tests 186
3.14.2 Tests Addressing Reactivity Insertion Accidents 194
3.14.2.1 Power Burst Facility Test RIA-ST-4 195
3.14.2.2 JAERI Tests in the Nuclear Safety Research Reactor 198
3.14.2.3 JAERI Out-of-Pile Tests 201

Chapter 4 Melt Breakup, Entrainment, Mixing, and Fragmentation 203

4.1 Coarse Mixing Prior to the Onset of a Vapor Explosion 204
4.1.1 Melt Breakup and Coarse Mixing in Film Boiling 205
4.1.2 Transient Considerations for Coarse Fragmentation 210
4.1.3 Scaling Parameters for Melt Breakup and Coarse Mixing in Film Boiling 213
4.1.4 Experiments Related to Coarse Mixing and Water Depletion in Film Boiling 215
4.1.4.1 MIXA Experiments 215
4.1.4.2 MAGICO Experiments 219
4.1.4.3 QUEOS Experiments 221
4.1.5 Comments Related to Coarse Mixing in Steam Explosion Experiments 223
4.1.5.1 The Sandia Large-Scale Aluminum–Water Experiments 223
4.1.5.2 The KROTOS Alumina–Water Experiments 224
4.2 Fine-Scale Fragmentation: Breakup of Drops in High-Velocity Flows 231
4.3 Liquid–Liquid Fragmentation and Mixing 233
4.4 Drag Coefficients for Dense Dispersions 239
4.5 Influence of Freezing a Crust on a Molten Jet 243
4.6 Possible Influence of Gas Blow-Through on Liquid Fragmentation in the MFMI Tests 248
4.6.1 Experimental Features of the MFMI Tests 248
4.6.2 Melt Fragmentation in the MFMI-1 Tests 250
4.6.3 Melt Fragmentation in the MFMI-4 Test 252
4.7 A Summary Statement on Thermal Explosions 254

Chapter 5 The Magnitude of Combined Physical and Chemical Explosions . . 257

5.1 A Mechanism for a Steam–Metal Chemical Explosion with Highly Reactive Metals . . . 257

5.2 Summary of Aluminum–Water Explosion Experiments in Which Chemical Explosions Were Observed . . . 257

5.2.1 Hess et al. Externally Triggered Tests . . . 257

5.2.2 Battelle Columbus Aluminum–Water Tests . . . 259

5.2.3 Sandia National Laboratory NPR Tests . . . 261

5.3 The Possible Role of Hydrogen in Causing a Chemical Explosion . . . 266

5.3.1 Hydrogen Produced during Coarse Premixing Prior to the Explosion . . . 266

5.3.2 Hydrogen Dissolved during the Dwell Time Prior to the Explosion . 269

5.3.3 Additional Observations from the SNL Tests . . . 279

5.4 Heat Flux Leaving the Aluminum Droplets . . . 282

5.5 Molten Aluminum–Water Shock Tube Experiments . . . 283

5.5.1 UCSB Shock Tube Experiments . . . 283

5.5.2 University of Wisconsin Shock Tube Experiments . . . 284

5.6 Steam Explosion Experiments with Other Highly Reactive Metals . . . 293

5.6.1 Copper–Water Steam Explosion Experiments . . . 293

5.6.2 Zirconium–Water Experiments . . . 296

Chapter 6 BORAX, SPERT, and the SL-1 Accident . . . 298

6.1 Background . . . 298

6.2 Relationship of BORAX, SPERT, and SL-1 to the Explosive Mechanisms Discussed in Chapters 3 and 5 . . . 299

6.3 BORAX-1 Experiment . . . 303

6.4 SPERT-1 Experiment . . . 307

6.5 SL-1 Accident . . . 314

6.6 Summary . . . 320

Chapter 7 Consistency throughout the Experimental Database . . . 322

7.1 The Hot Liquid Must Be Greater Than a Minimum Temperature . . . 322

7.2 Consistency between the Demonstration of No Significant Hydrodynamic Mixing and CMCR Bounding of the Available Data for Non–Chemically Reactive Systems . . . 324

7.3 Consistency between Maximum Temperature Required to Initiate an Explosion and the Contact Interface Temperature . . 325

7.4 Consistency between the Required Nucleation Process for an Explosion and the Observation That a Relatively Small Overpressure Can Prevent an Explosion . . . 326

7.5 Consistency between the MAGICO, MIXA, and QUEOS Experiments with Respect to the Influence of Water Depletion 327
7.6 Consistency with Observations That the Forced Contact Mode Causes Direct Entrainment and Energy Transfer That Prevents the Accumulation of Masses with a Substantial Temperature Difference 327
7.7 Consistency between SNL Tests and KROTOS with Respect to the Difference between Alumina Melts and Corium Melts 328
7.8 CMCR Approach Easily Translates to a Quantified Explanation of the SNL NRP Experiments, BORAX-1, SPERT-1, and the SL-1 Accident 328

Chapter 8 Summary and Conclusions 330
8.1 General Behavioral Principles 330
8.2 Potential for Vapor Explosions with Sodium and Molten UO_2 331
8.3 The Effective Efficiencies (Conversion Ratio) for Steam Explosions 332
8.4 The Mixing Processes to Be Considered for Vapor/Steam Explosions 333
8.5 The Potential for Steam Explosions to Transition into a Chemical Explosion 334

Appendix A Simplified Representation of the Homogeneous Nucleation Temperature for a Liquid 337
Appendix B Work Done by Vaporization 341
Appendix C Material Properties Used in the Analyses 344

References. 347

About the Authors 367