

TABLE OF CONTENTS

| | |
|--------------------------------|-------------|
| Acknowledgments | iii |
| Contributor Biographies | v |
| Preface | xvii |

Chapter 1 Evolution of Power Reactors and Containments

| | |
|---|----------|
| <i>Hansraj Ashar</i> | 1 |
| 1.1 Introduction | 1 |
| 1.2 Steps toward Development of Commercial Nuclear Reactors | 2 |
| 1.3 Reactor Concepts and Containments | 4 |
| 1.3.1 Pressurized Water Reactors | 5 |
| 1.3.2 Boiling Water Reactors | 6 |
| 1.4 Containment and Containment Structures | 7 |
| 1.4.1 PWR Containments | 7 |
| 1.4.1.1 Large Dry PWR Containments | 9 |
| 1.4.1.2 PWR Subatmospheric Containments | 9 |
| 1.4.1.3 PWR Ice Condenser Containments | 12 |
| 1.4.2 BWR Containments | 12 |
| 1.4.2.1 Early BWR Containments | 12 |
| 1.4.2.2 BWR Mk I Containments | 14 |
| 1.4.2.3 BWR Mk II Containments | 17 |
| 1.4.2.4 BWR Mk III Containments | 18 |
| Appendix 1A — Plant Specific Information | 19 |
| References | 22 |

Chapter 2 Regulatory Requirements and Containments

| | |
|---|-----------|
| <i>Hansraj Ashar</i> | 23 |
| 2.1 Introduction (Historical Background) | 23 |
| 2.2 Development of Regulations | 25 |
| 2.3 Regulatory Frameworks | 25 |
| 2.3.1 Guidance Documents and Reports | 26 |
| 2.3.1.1 Regulatory Guides (RGs) | 26 |
| 2.3.1.2 Standard Review Plan (SRP) | 26 |
| 2.3.1.3 NUREG-Series Reports | 26 |
| 2.3.1.4 Other NRC Documents | 27 |
| 2.4 Technical Parts of Chapter 1 of Title 10 | 27 |
| 2.4.1 Requirements of Parts 20 and 21 | 27 |
| 2.4.2 Requirements of Part 50 and Its Subsections | 27 |
| 2.4.3 Requirements of Part 50 Appendices | 31 |
| 2.4.4 Requirements of Part 52 to Part 100 | 34 |

| | |
|---|----|
| 2.5 Containment-Related Regulations | 35 |
| 2.5.1 Reactor Site Criteria | 35 |
| 2.5.2 General Design Criteria | 37 |
| 2.5.3 Implementation of Containment-Related GDC | 37 |
| References | 43 |

Chapter 3 Design, Construction, Inspection and Testing of Containment Structures

| | |
|--|-----------|
| <i>Javeed Munshi, Shen Wang and Abdul Sheikh</i> | 45 |
| 3.1 Concrete Containments | 45 |
| 3.1.1 Introduction | 45 |
| 3.1.2 Conventionally Reinforced Concrete Containments | 46 |
| 3.1.3 Prestressed Concrete Containments | 46 |
| 3.1.4 Modeling and Analysis Considerations | 47 |
| 3.1.5 Concrete Containment Design Criteria | 48 |
| 3.1.6 Design Considerations for Prestressed Containments | 49 |
| 3.1.7 Liner and Liner Anchor Design | 51 |
| 3.1.8 Pre-Service Inspection and Testing (Concrete) | 51 |
| 3.1.9 Severe Accident Analysis | 53 |
| 3.2 Steel Containments | 54 |
| 3.2.1 Introduction | 54 |
| 3.2.2 Modeling and Analysis Considerations | 55 |
| 3.2.3 Steel Containment Design Criteria | 55 |
| 3.2.4 Buckling Analysis | 57 |
| 3.2.5 Severe Accident Evaluation | 57 |
| 3.2.6 Fabrication and Installation | 58 |
| 3.2.7 Pre-Service Inspection and Testing | 58 |
| 3.3 Containment Evaluation for Impact and Impulse | 59 |
| 3.3.1 Evaluation of Local Effect | 60 |
| 3.3.2 Evaluation of Global Response | 60 |
| 3.3.3 Finite Element Analysis | 61 |
| 3.3.4 Special Consideration for Aircraft Impact Assessment | 61 |
| References | 62 |

Chapter 4 Inservice Inspections and Leak Rate Testing of Containments

| | |
|---|-----------|
| <i>Hansraj Ashar</i> | 67 |
| 4.1 Introduction | 67 |
| 4.2 Purpose of Periodic ISI and Leak Rate Testing | 68 |
| 4.3 Deterministic Approach | 68 |
| 4.3.1 Containment Inservice Inspection | 68 |
| 4.3.1.1 ASME Code | 69 |
| 4.3.1.2 Requirements of Subsection IWE | 69 |
| 4.3.1.3 Requirements of Subsection IWL | 72 |
| 4.3.2 Prescriptive Leak Rate Testing Requirements | 74 |
| 4.3.2.1 Type A Testing | 75 |
| 4.3.2.2 Type B Testing | 76 |
| 4.3.2.3 Type C Tests | 76 |
| 4.3.2.4 Other Requirements | 77 |
| 4.4 Performance Based Approach (PBA) | 77 |
| 4.4.1 Inservice Inspections and PBA | 77 |

| | |
|--|----|
| 4.4.2 Leak Rate Testing and PBA | 78 |
| 4.4.2.1 Type A Test Requirements | 78 |
| 4.4.2.2 Type B Test Requirements | 79 |
| 4.4.2.3 Type C Test Requirements | 79 |
| 4.4.3 Risk Informed Approach (RIA) | 79 |
| 4.4.3.1 Discussion of RIA Issues | 81 |
| 4.4.3.2 Industry Actions on ILRT Intervals | 82 |
| 4.5 Miscellaneous Remarks | 85 |
| References | 86 |

Chapter 5 License Renewal and Aging Management for Continued Service

| | |
|---|-----------|
| <i>Dan Naus and Hansraj Ashar</i> | 89 |
| 5.1 Introduction | 89 |
| 5.2 License Renewal Process, Safety Principles, and Regulations | 89 |
| 5.2.1 10 CFR Part 54 (Rule) | 90 |
| 5.2.2 10 CFR Part 51 | 91 |
| 5.3 Guidance Documents | 91 |
| 5.3.1 NRC Guidance Documents | 91 |
| 5.3.1.1 Regulatory Guide 1.188, Revision 1 | 92 |
| 5.3.1.2 Generic Aging Lessons Learned (GALL) Report | 92 |
| 5.3.1.3 Standard Review Plan for License Renewal (SRP-LR) | 94 |
| 5.3.1.4 Nuclear Plant Aging Research (NPAR) Reports | 95 |
| 5.3.1.5 Technical Reports in NUREG Series (NUREGs) | 95 |
| 5.3.2 Industry Guidance Documents | 95 |
| 5.3.2.1 NUMARC Reports | 95 |
| 5.3.2.2 NEI 95-10 | 96 |
| 5.4 License Renewal Inspections | 96 |
| 5.5 Operating Experience | 97 |
| References | 98 |
| Appendix 5A Monitoring and Trending of Prestressing Forces in Prestressed Concrete Containments | 101 |
| 5A.1 Introduction | 102 |
| 5A.2 Construction and Design Features | 102 |
| 5A.2.1 Prestressing Systems | 102 |
| 5A.2.2 Corrosion Inhibitors for Prestressing Tendons | 103 |
| 5A.2.2.1 Portland Cement Grout | 104 |
| 5A.2.2.2 Petrolatum-Based Grease | 104 |
| 5A.2.3 Design Considerations | 105 |
| 5A.3 Factors Contributing to Prestress Losses | 105 |
| 5A.3.1 Shrinkage of Concrete | 105 |
| 5A.3.2 Creep of Concrete | 105 |
| 5A.3.3 Relaxation of Prestressing Steel | 106 |
| 5A.3.4 Losses Caused by Degradation of Prestressing Elements | 106 |
| 5A.3.5 Effects of Temperature | 106 |
| 5A.4 Monitoring Prestressing Forces | 107 |
| 5A.4.1 Grouted or Bonded Tendons | 107 |
| 5A.4.2 Greased or Unbonded Tendons | 107 |
| 5A.5 Trending Prestressing Forces | 108 |
| 5A.5.1 Bonded Tendons | 108 |
| 5A.5.2 Unbonded Tendons | 108 |

| | |
|---|-----|
| 5A.6 Discussion | 109 |
| 5A.7 Concluding Remarks | 110 |
| References | 111 |
| Appendix 5B Summary of Major Degradation in Containments | 113 |
| 5B.1 Introduction | 113 |
| 5B.2 Reinforced Concrete Containments and Steel Liners | 113 |
| 5B.2.1 Post-Tensioning System | 113 |
| 5B.2.2 Concrete Containment Vessel | 114 |
| 5B.2.3 Steel Liner | 118 |
| 5B.3 Steel Containments | 120 |
| 5B.3.1 BWR Free-Standing Steel Containment | 120 |
| 5B.3.2 Steel Cylinder of PWR Ice-Condenser Primary Containments | 121 |
| 5B.3.3 Torus of BWR MK I Plants | 121 |
| References | 124 |

Chapter 6 Containment Structure Testing, Modeling, and Degradation

| | |
|--|------------|
| <i>Jason Petti</i> | 125 |
| 6.1 Introduction | 125 |
| 6.2 Early Estimates of Containment Structural Response to Severe Accidents | 126 |
| 6.3 Large-Scale Containment and Component Testing | 127 |
| 6.3.1 Containment Testing Purpose | 128 |
| 6.3.2 Containment Tests | 128 |
| 6.3.2.1 Reinforced Concrete Containment Tests | 128 |
| 6.3.2.2 Prestressed Concrete Containment Tests | 130 |
| 6.3.2.3 Steel Containment Tests | 133 |
| 6.3.2.4 Containment Component Testing | 135 |
| 6.4 Containment Severe Accident Modeling and Insights | 138 |
| 6.4.1 Concrete Containment Analyses | 138 |
| 6.4.2 Steel Containment Analyses | 140 |
| 6.4.3 Probabilistic Modeling of Containment Severe Accident Response | 141 |
| 6.5 Effects of Containment Degradation on Its Severe Accident Response | 142 |
| 6.5.1 Examples of Deterministic Modeling | 142 |
| 6.5.1.1 PWR Ice Condenser Steel Containment | 143 |
| 6.5.1.2 BWR Mark I Steel Containment | 144 |
| 6.5.1.3 PWR Reinforced Concrete Containment | 146 |
| 6.5.1.4 PWR Prestressed Concrete Containment | 146 |
| 6.5.2 Probabilistic Analysis of Degradation Effects | 148 |
| 6.5.2.1 PWR Ice Condenser Steel Containment | 149 |
| 6.5.2.2 BWR Mark I Steel Containment | 150 |
| 6.5.2.3 PWR Reinforced Concrete Containment | 151 |
| 6.5.2.4 PWR Prestressed Concrete Containment | 153 |
| 6.5.3 Risk-Informed Assessment of Degraded Containments | 155 |
| 6.5.4 Containment Degradation Effects on Severe Accident Consequences | 156 |
| References | 158 |

Chapter 7 Containment System Challenges Under Severe Accidents

| | |
|---|------------|
| <i>Dana Powers, Shawn Burns and Hansraj Ashar</i> | 163 |
| 7.1 Introduction | 164 |

| | |
|--|-----|
| 7.2 Hydrogen Combustion | 164 |
| 7.2.1 Hydrogen Sources | 164 |
| 7.2.2 Modes of Combustion | 165 |
| 7.2.2.1 Deflagrations | 166 |
| 7.2.2.2 Detonations | 169 |
| 7.2.2.3 Deflagration to Detonation Transitions | 170 |
| 7.2.3 Hydrogen Combustion Mitigation | 171 |
| 7.3 Core Debris Interactions with Coolant | 171 |
| 7.3.1 Core Debris Quenching | 171 |
| 7.3.2 Explosive Interactions of Core Debris with Water | 172 |
| 7.4 High Pressure Melt Expulsion and Direct Containment Heating | 178 |
| 7.4.1 Experimental and Analytic Investigations of Direct Containment Heating | 180 |
| 7.4.2 Resolution of the Direct Containment Heating Issue | 183 |
| 7.4.3 Ongoing Research | 184 |
| 7.5 Interaction of Core Debris with Concrete | 184 |
| 7.5.1 Nature of Ex-Vessel Core Debris | 185 |
| 7.5.2 Nature of Concrete | 186 |
| 7.5.3 Experimental Investigations of Core Debris Interactions with Concrete | 186 |
| 7.5.4 Modeling Core Debris Interactions with Concrete | 188 |
| 7.5.5 Mitigation of Core Debris Interactions with Concrete | 189 |
| 7.6 Aerosol Behavior in Reactor Containments | 191 |
| 7.6.1 Aerosol Formation and Growth | 192 |
| 7.6.2 Natural Particle Removal Processes | 192 |
| 7.6.3 Effects of Engineered Safety Features | 194 |
| 7.6.4 Aerosol Leakage Out of Containment | 195 |
| 7.6.5 Filtered Vents | 196 |
| 7.7 Gaseous Iodine in Containment | 196 |
| 7.8 Consideration of Severe Accidents in Regulatory Framework | 199 |
| 7.8.1 Operating Reactors | 199 |
| 7.8.2 Advanced Reactors | 200 |
| References | 202 |

Chapter 8 Design Basis and Beyond Design Basis Considerations of Natural Phenomena

| | |
|---|------------|
| <i>Nilesh Chokshi and Goutam Bagchi</i> | 211 |
| 8.1 Introduction | 211 |
| 8.2 Summary of Design Basis for Natural Phenomena | 212 |
| 8.2.1 Key Regulations Related to Containment Design | 213 |
| 8.2.2 Seismic | 214 |
| 8.2.3 Flooding | 214 |
| 8.2.4 High Winds | 215 |
| 8.2.5 Other Natural Hazards | 215 |
| 8.3 Design Basis and Beyond Design Basis Events | 215 |
| 8.3.1 Historical Perspective | 215 |
| 8.3.2 Evolution of Hazard Understanding | 216 |
| 8.3.2.1 Seismic | 216 |
| 8.3.2.2 Flooding | 217 |
| 8.3.2.3 High Winds | 218 |

| | |
|--|-----|
| 8.3.3 Recent Experiences Related to Natural Phenomena Hazards | 220 |
| 8.3.3.1 Seismic Experience | 220 |
| 8.3.3.2 Flood Experience | 223 |
| 8.3.4 Risk-Informed Considerations | 225 |
| 8.4 Methods for Beyond Design Basis Evaluations | 225 |
| 8.4.1 Historical Perspective — Evolution of Methods | 225 |
| 8.4.2 Seismic Probabilistic Risk Assessment (SPRA) Methods | 226 |
| 8.4.2.1 General | 226 |
| 8.4.2.2 Probabilistic Seismic Hazard Analysis | 228 |
| 8.4.2.3 Fragility Analysis | 228 |
| 8.4.2.4 Systems Analysis and Quantification | 229 |
| 8.4.3 Containment Capacity and Fragility Analysis | 230 |
| 8.4.3.1 Seismic Capacity and Fragility Analysis | 230 |
| 8.4.3.2 Internal Pressure Capacity and Fragility Analysis | 235 |
| 8.4.4 Examples and Insights Related to Containment Performance | 238 |
| 8.4.5 Consideration for New Reactors | 239 |
| 8.4.6 Methods for Other Natural Hazards | 240 |
| 8.5 Current Initiatives Following the Fukushima Event | 241 |
| 8.6 Summary and General Conclusions | 246 |
| Acknowledgments | 246 |
| References | 246 |

Chapter 9 Evolution of Containment Systems for Gen III Reactors

| | |
|--|------------|
| <i>Jim Xu</i> | 251 |
| 9.1 Introduction | 251 |
| 9.2 Regulatory Perspectives for Generation III/III+ Reactors | 252 |
| 9.2.1 Part 52 Regulatory Process | 252 |
| 9.2.2 Standardization of Reactor Designs | 253 |
| 9.3 Design and Analysis Considerations for Standard Designs | 255 |
| 9.3.1 Structural Aspects of Standardized Designs | 255 |
| 9.3.2 Technical Considerations and Challenges in Structural Designs and Analyses | 258 |
| 9.3.2.1 Certified Seismic Design Response Spectra (CSDRS) and Associated Generic Site Conditions for Design Certification | 259 |
| 9.3.2.2 Structural Models for Seismic Analysis | 261 |
| 9.3.2.3 Stability Evaluation for Seismic Design | 261 |
| 9.3.2.4 Considerations of Settlement Effect in Standard Designs | 262 |
| 9.4 Containment Features of Generation III/III+ Reactors | 264 |
| 9.4.1 Advances of Generation III/III+ Reactor Designs | 264 |
| 9.4.2 Generation III/III+ BWR Designs | 265 |
| 9.4.2.1 ABWR | 265 |
| 9.4.2.2 ESBWR | 267 |
| 9.4.3 Generation III/III+ PWR Designs | 271 |
| 9.4.3.1 AP1000 | 271 |
| 9.4.3.2 US EPR | 276 |
| 9.4.3.3 US APWR | 281 |
| References | 285 |

Appendix A Glossary of NPP-Related Terms