

Contents

| | |
|--|-----|
| Preface | iii |
| 1. Executive Summary..... | 1 |
| 1.1 Introduction | 1 |
| 1.2 Formulating Responses to Nuclear or Radiological Incidents | 4 |
| 1.3 Late-Phase Recovery: A Challenging Journey to Resume Normal Life..... | 5 |
| 1.4 Optimizing Decision Making: A Framework and Process .. | 7 |
| 1.5 Stakeholder Engagement in Decision Making | 9 |
| 1.6 Managing Long-Term Contamination | 11 |
| 1.7 Path Forward and Recommendations..... | 12 |
| 2. Introduction..... | 14 |
| 2.1 Purpose | 14 |
| 2.2 Target Audiences | 16 |
| 2.3 Scope..... | 16 |
| 2.4 Approach to Optimization | 18 |
| 2.4.1 Late-Phase Recovery Considerations | 18 |
| 2.4.2 Principle of Optimization of Radiation Protection: Approach and Implementation | 19 |
| 2.5 Lessons Learned from Past Incidents..... | 21 |
| 2.6 Relationship to Other NCRP Documents | 22 |
| 2.7 Report Structure..... | 23 |
| 3. Description of Major Nuclear or Radiological Incidents with Long-Term Contamination | 25 |
| 3.1 Introduction | 25 |
| 3.2 Description of Major Historic Nuclear or Radiological Incidents | 26 |
| 3.2.1 Accidents Associated with Nuclear Facilities .. | 26 |
| 3.2.1.1 Mayak Nuclear Facilities Accident: The Kyshtym Accident (1957)..... | 26 |
| 3.2.1.2 Chernobyl Nuclear Reactor Accident (1986) | 27 |
| 3.2.1.3 Fukushima Dai-ichi NPP Accident (2011) | 27 |
| 3.2.2 Incidents Involving Radioactive Materials: The Goiânia Radiological Accident (1987) | 28 |
| 3.3 Nuclear or Radiological Incidents from Terrorist Acts .. | 29 |

| | | |
|------------------|--|----|
| 3.3.1 | Radiological and Nuclear Terrorism | 29 |
| 3.3.1.1 | Radiological Dispersal Devices | 30 |
| 3.3.1.2 | Improvised Nuclear Devices | 30 |
| 3.3.2 | Incident Progression and Radiological Characteristics..... | 32 |
| 3.3.2.1 | Incidents Associated with an RDD ... | 32 |
| 3.3.2.1.1 | Radioactive Sources | 32 |
| 3.3.2.1.2 | Beta-Particle/Gamma-Ray Sources | 32 |
| 3.3.2.1.3 | Alpha-Particle Sources | 33 |
| 3.3.2.1.4 | Radiopharmaceuticals and Biomedical Research Radionuclides | 34 |
| 3.3.2.1.5 | Dispersal Characteristics ... | 34 |
| 3.3.2.2 | Incidents Associated with an IND | 34 |
| 3.3.2.2.1 | Radionuclide Concerns | 34 |
| 3.3.2.2.2 | Fallout Characteristics | 36 |
| 3.3.3 | Magnitude of Radioactive Contamination | 36 |
| 3.4 | Incident Phases for Response and Recovery | 37 |
| 3.4.1 | Phases of Incidents | 38 |
| 3.4.1.1 | Short-Term Phase Contrasted with the Early Phase | 39 |
| 3.4.1.2 | Intermediate Phase Contrasted with the Intermediate Phase..... | 39 |
| 3.4.1.3 | Long-Term Phase Contrasted with the Late Phase..... | 40 |
| 3.4.2 | Protective Actions | 41 |
| 3.4.2.1 | Protective Action Guides | 41 |
| 3.4.2.2 | Early-Phase Protection Action Guides. | 41 |
| 3.4.2.3 | Intermediate-Phase PAGs | 41 |
| 3.4.2.4 | Late-Phase Site-Specific Optimization | 42 |
| 4. | Decision Framework in Late-Phase Recovery | 44 |
| 4.1 | Late-Phase Recovery..... | 44 |
| 4.1.1 | Objective of Recovery | 44 |
| 4.1.2 | Late-Phase Considerations..... | 44 |
| 4.1.3 | Resilience of Recovery..... | 45 |
| 4.2 | Key Issues in Late-Phase Recovery | 46 |
| 4.2.1 | Issues Affecting the Society | 47 |
| 4.2.2 | Issues Related to Radioactive Contamination ... | 49 |
| 4.2.2.1 | Addressing a Multitude of Radiological Issues..... | 49 |
| 4.2.2.2 | Management of Radioactive Waste ... | 50 |

| | | |
|------------------|---|-----------|
| 4.2.2.2.1 | Issues Associated with Existing Systems for Management of Radioactive Waste | 50 |
| 4.2.2.2.2 | Unique Need for Temporary Storage of Radioactive Waste After Major Incidents | 51 |
| 4.2.2.2.3 | Considerations for Management of Radioactive Waste Generated from Materials Outside of Atomic Energy Act Processes and Activities | 52 |
| 4.2.2.3 | Management of Commodities and Drinking Water..... | 53 |
| 4.2.3 | Long-Term Issues and Management Considerations | 54 |
| 4.3 | Site-Specific Optimization Framework in Decision Making | 55 |
| 4.3.1 | Basis of Decision Making..... | 55 |
| 4.3.2 | Principle of Optimization..... | 56 |
| 4.3.3 | Optimization Process | 58 |
| 4.3.4 | Guidance on Optimization | 59 |
| 4.3.4.1 | Principle of Optimization..... | 59 |
| 4.3.4.2 | Long-Term Monitoring and Management..... | 59 |
| 4.3.5 | Cleanup Criteria and Standards | 60 |
| 4.4 | Steps Toward Long-Term Recovery | 61 |
| 4.4.1 | Recovery Planning | 61 |
| 4.4.1.1 | Pre-incident Recovery Planning | 61 |
| 4.4.1.2 | Post-Incident Recovery Planning | 63 |
| 4.4.2 | Remediation of Contamination | 65 |
| 5. | Implementation of the Optimization Framework for Decision Making | 66 |
| 5.1 | Role of Optimization in the Decision-Making Process .. | 66 |
| 5.1.1 | Role of Optimization in the Decision-Making Process..... | 66 |
| 5.1.1.1 | Decision Team..... | 67 |
| 5.1.1.2 | Recovery-Management Team | 68 |
| 5.1.1.3 | Technical Working Group | 69 |
| 5.1.1.4 | Stakeholder Working Group | 69 |
| 5.1.2 | Evaluating Societal Needs | 71 |
| 5.1.3 | Acceptance of Decisions | 72 |
| 5.2 | Defining Post Incident Conditions | 74 |
| 5.2.1 | Characterizing Contamination | 74 |
| 5.2.2 | Defining the Affected Area..... | 75 |

| | | |
|------------------|---|-----|
| 5.2.3 | Essential Services | 76 |
| 5.2.4 | Identifying Land Use..... | 76 |
| 5.2.5 | Understanding Demographics | 78 |
| 5.3 | Assess Impact | 78 |
| 5.3.1 | Characterizing Risks..... | 78 |
| 5.3.1.1 | Industrial Property | 80 |
| 5.3.1.2 | Commercial Property | 81 |
| 5.3.1.3 | Residential Property..... | 81 |
| 5.3.2 | Site-Specific Conditions | 81 |
| 5.3.3 | Data and Information Requirements..... | 82 |
| 5.3.4 | Environmental Risk Assessment Tools | 82 |
| 5.4 | Establish Goals and Identify Options | 93 |
| 5.4.1 | Establishing Goals..... | 93 |
| 5.4.1.1 | Variety of Goals..... | 93 |
| 5.4.1.2 | Long-Term Health and Environmental Protection..... | 95 |
| 5.4.2 | Identifying Options | 95 |
| 5.4.2.1 | Options for Inhabited Areas..... | 95 |
| 5.4.2.2 | Shielding Options | 96 |
| 5.4.2.3 | Types of Shielding..... | 96 |
| 5.4.2.4 | Removal Options..... | 96 |
| 5.4.2.5 | Self-Help Actions..... | 97 |
| 5.4.2.6 | Decision Not to Implement Any Recovery Options..... | 97 |
| 5.4.2.7 | Options for Food Production and Drinking Water Supplies | 97 |
| 5.4.2.7.1 | Intervention Along the Soil-to-Plant Pathway..... | 98 |
| 5.4.2.7.2 | Intervention in Animal Production Systems | 99 |
| 5.4.2.7.3 | Intervention in Drinking Water Supplies..... | 99 |
| 5.4.2.7.4 | Reassurance | 99 |
| 5.4.2.8 | Waste Disposal Options | 99 |
| 5.4.2.9 | Options for Forest Areas..... | 100 |
| 5.5 | Evaluating Options..... | 100 |
| 5.5.1 | Technical Approaches to Supporting Decision Making | 101 |
| 5.5.1.1 | Cost-Benefit Analysis | 101 |
| 5.5.1.2 | Other Economic Models | 103 |
| 5.5.2 | Stakeholder Involvement in Evaluating Options..... | 104 |
| 5.5.2.1 | Holistic Approach | 104 |
| 5.5.2.2 | Whole-Community Approach | 105 |
| 5.5.2.3 | Dynamic System | 106 |

CONTENTS / xi

| | | |
|----------------|---|-----|
| 5.5.2.4 | Fear | 107 |
| 5.5.2.5 | Psychological Impacts of Terrorist Incidents | 107 |
| 5.6 | Making Decisions | 108 |
| 5.6.1 | Regulatory Structure | 108 |
| 5.6.2 | Integrating Stakeholders in Decision Making .. | 109 |
| 5.6.3 | Approaches to Effective Risk Communication During Late-Phase Recovery | 111 |
| 5.7 | Implementing Decisions | 112 |
| 5.7.1 | Transparency of Decision Making | 112 |
| 5.7.2 | Effective Communication During Implementation | 113 |
| 5.7.2.1 | Delivery Channels | 114 |
| 5.7.2.2 | Use of Social Media | 114 |
| 5.7.3 | Program of Implementation | 115 |
| 5.8 | Monitor and Evaluate | 116 |
| 6. | Long-Term Management of Radioactive Contamination | 117 |
| 6.1 | Introduction | 117 |
| 6.2 | Long-Term Monitoring | 117 |
| 6.3 | Timeframe | 119 |
| 6.4 | Health Monitoring | 120 |
| 6.4.1 | Monitoring Considerations | 120 |
| 6.4.2 | Psychological Assessment | 122 |
| 6.4.3 | Registries | 126 |
| 6.4.4 | Resource Requirements and Infrastructure Needs | 128 |
| 6.5 | Food and Other Commodities | 129 |
| 6.5.1 | Food, Water and Agriculture | 129 |
| 6.5.1.1 | Food | 129 |
| 6.5.1.2 | Water | 132 |
| 6.5.1.3 | Projected Changes in Uses of Agricultural and Pasture Lands | 133 |
| 6.5.2 | Other Commodities and Critical Infrastructure | 134 |
| 6.5.2.1 | Medical Products | 134 |
| 6.5.2.2 | Consumer Products | 135 |
| 6.5.2.3 | Industrial | 135 |
| 6.5.2.4 | Critical Infrastructure and Property | 135 |
| 6.5.3 | Release of Other Properties | 136 |
| 6.5.3.1 | Surface Contamination | 137 |
| 6.5.3.2 | Volume Contamination | 142 |
| 6.6 | Economic Monitoring | 143 |
| 6.7 | Environmental Monitoring and Cessation of Monitoring | 146 |

| | | |
|--|--|------------|
| 6.8 | Long-Term Management | 147 |
| 6.8.1 | Food and Agriculture..... | 147 |
| 6.8.2 | Water | 148 |
| 6.8.3 | Forests and Recreation Areas..... | 149 |
| 7. | Summary of Recommendations | 150 |
| 7.1 | National Strategy Promoting Community Resilience... | 151 |
| 7.2 | Late-Phase Response Integration into Emergency Planning | 152 |
| 7.3 | Site-Specific Optimization | 154 |
| 7.4 | Stakeholder Engagement and Empowerment..... | 158 |
| 7.5 | Communication Plan | 160 |
| 7.6 | Adaptive and Responsive Cleanup Strategies..... | 162 |
| 7.7 | Research and Development | 168 |
| 7.8 | Continuous Adaptive Learning | 172 |
| Appendix A. Lessons Learned from Historic Incidents | | 174 |
| A.1 | Introduction and the International Nuclear and Radiological Event Scale | 174 |
| A.2 | Lessons from Nuclear or Radiological Incidents..... | 176 |
| A.2.1 | Nuclear Power Plant Accident at Fukushima, Japan (2011) | 178 |
| A.2.1.1 | Description of the Incident..... | 178 |
| A.2.1.2 | Summary of Impacts..... | 178 |
| A.2.1.2.1 | Radiation Exposures..... | 178 |
| A.2.1.2.2 | Contamination of Land.... | 179 |
| A.2.1.2.3 | Contamination of Foodstuffs | 179 |
| A.2.1.2.4 | Environmental Contamination | 180 |
| A.2.1.3 | Summary of Long-Term Recovery ... | 180 |
| A.2.1.4 | Special Aspects of the Incident..... | 181 |
| A.2.1.5 | Lessons Learned | 181 |
| A.2.2 | Poisoning of Alexander Litvinenko with ^{210}Po in London (2006) | 182 |
| A.2.2.1 | Description of the Incident..... | 182 |
| A.2.2.2 | Summary of Impacts..... | 183 |
| A.2.2.3 | Summary of Long-Term Recovery ... | 185 |
| A.2.2.3.1 | Cleanup Criteria..... | 185 |
| A.2.2.3.2 | Approach to Environmental Remediation and Technology..... | 185 |
| A.2.2.3.3 | Mobile Contamination | 186 |
| A.2.2.3.4 | Fixed Contamination | 186 |

| | | |
|----------------|--|-----|
| | A.2.2.3.5 Waste Management and Disposal | 187 |
| | A.2.2.3.6 Stakeholder Involvement and Communication | 187 |
| A.2.2.4 | Special Aspects of the Incident | 187 |
| A.2.2.5 | Lessons Learned..... | 188 |
| A.2.3 | Cesium-137 Source Accident, Goiânia, Brazil (1987)..... | 188 |
| | A.2.3.1 Description of the Incident | 188 |
| | A.2.3.2 Summary of Impacts | 189 |
| | A.2.3.3 Summary of Long-Term Recovery.... | 189 |
| | A.2.3.4 Special Aspects of the Incident | 190 |
| | A.2.3.5 Lessons Learned..... | 190 |
| A.2.4 | Chernobyl Nuclear Reactor Accident (1986)... | 191 |
| | A.2.4.1 Description of the Incident | 191 |
| | A.2.4.1.1 Incident Scenario..... | 191 |
| | A.2.4.1.2 Radioactive Contamination | 192 |
| | A.2.4.1.3 Environmental Transport . | 192 |
| | A.2.4.1.4 Affected Populations and the Area | 193 |
| | A.2.4.2 Summary of Impacts | 193 |
| | A.2.4.2.1 Health Effects | 194 |
| | A.2.4.2.2 Cleanup Costs | 194 |
| | A.2.4.2.3 Psychological and Other Effects..... | 194 |
| | A.2.4.3 Summary of Long-Term Recovery.... | 195 |
| | A.2.4.3.1 Late-Phase Recovery Issues | 195 |
| | A.2.4.3.2 Cleanup Criteria: Belarus, Russia and Ukraine..... | 196 |
| | A.2.4.3.3 Cleanup Criteria: Norway . | 197 |
| | A.2.4.4 Approach to Environmental Remediation and Technology..... | 197 |
| | A.2.4.4.1 Inhabited Areas | 197 |
| | A.2.4.4.2 Food Production Systems . | 198 |
| | A.2.4.4.3 Forest Ecosystems | 198 |
| | A.2.4.4.4 Aquatic Ecosystems..... | 198 |
| | A.2.4.5 Waste Management and Disposal ... | 198 |
| | A.2.4.6 Stakeholder Involvement and Communication | 199 |
| | A.2.4.7 Lessons Learned..... | 199 |
| A.2.5 | Three Mile Island Nuclear Accident in Dauphin County, Pennsylvania (1979)..... | 200 |
| | A.2.5.1 Description of the Incident | 200 |
| | A.2.5.2 Summary of Impacts | 200 |

| | | |
|------------------|---|-----|
| A.2.5.3 | Summary of Long-Term Recovery | 201 |
| A.2.5.4 | Special Aspects of the Incident. | 202 |
| A.2.5.5 | Lessons Learned | 202 |
| A.2.6 | Aircraft Accident Involving Thermonuclear Weapons, Near Palomares, Spain (1966) | 202 |
| A.2.6.1 | Description of the Incident | 202 |
| A.2.6.2 | Summary of Impacts. | 203 |
| A.2.6.3 | Summary of Long-Term Recovery | 204 |
| A.2.6.4 | Special Aspects of the Incident. | 204 |
| A.2.6.5 | Lessons Learned | 205 |
| A.2.7 | Windscale Fire (1957) | 205 |
| A.2.7.1 | Description of the Incident | 205 |
| A.2.7.1.1 | Incident Scenario | 206 |
| A.2.7.1.2 | Radioactive Contamination | 206 |
| A.2.7.1.3 | Affected Populations and Areas | 207 |
| A.2.7.2 | Summary of Impacts. | 207 |
| A.2.7.2.1 | Quantitative Impacts | 207 |
| A.2.7.2.2 | Health Effects | 208 |
| A.2.7.2.3 | Cleanup Costs | 208 |
| A.2.7.2.4 | Psychological Effects. | 208 |
| A.2.7.3 | Summary of Long-Term Recovery | 209 |
| A.2.7.3.1 | Late-Phase Recovery Issues | 209 |
| A.2.7.3.2 | Cleanup Criteria | 209 |
| A.2.7.3.3 | Approach to Environmental Remediation and Technology | 209 |
| A.2.7.3.4 | Waste Management and Disposal | 209 |
| A.2.7.3.5 | Stakeholder Involvement | 209 |
| A.2.7.4 | Special Aspects of the Incident. | 210 |
| A.2.7.5 | Lessons Learned | 210 |
| A.2.8 | Marshall Islands (1946 to 1958) | 211 |
| A.2.8.1 | Description of the Testing | 211 |
| A.2.8.1.1 | Incident Scenario | 211 |
| A.2.8.1.2 | Radioactive Contamination | 211 |
| A.2.8.1.3 | Affected Populations and Areas | 211 |
| A.2.8.2 | Summary of Impacts. | 212 |
| A.2.8.2.1 | Health Effects | 212 |
| A.2.8.2.2 | Cleanup Costs | 212 |
| A.2.8.2.3 | Psychological Effects. | 212 |
| A.2.8.3 | Summary of Long-Term Recovery | 213 |
| A.2.8.3.1 | Late-Phase Recovery Issues | 213 |

| | | |
|------------------|--|-----|
| A.2.8.3.2 | Cleanup Criteria | 213 |
| A.2.8.3.3 | Approach to Environmental Remediation and Technology | 213 |
| A.2.8.3.4 | Stakeholder Involvement and Communication | 213 |
| A.2.8.4 | Lessons Learned..... | 214 |
| A.2.9 | Liberty RadEx, a Recent Exercise in the United States Against Radiological Terrorism (2010) . | 214 |
| A.2.9.1 | Background..... | 214 |
| A.2.9.2 | Incident Scenario | 214 |
| A.2.9.3 | Objective | 215 |
| A.2.9.4 | Scope | 215 |
| A.2.9.5 | Summary of the Exercise..... | 216 |
| A.2.9.6 | Special Aspects of the Incident | 216 |
| A.2.9.7 | Lessons Learned..... | 216 |
| A.3 | Lessons from Nonradiological Incidents | 217 |
| A.3.1 | Hurricane Katrina Disaster (2005) | 217 |
| A.3.1.1 | Description of the Incident | 217 |
| A.3.1.2 | Summary of Impacts | 218 |
| A.3.1.2.1 | Economic Impacts | 218 |
| A.3.1.2.2 | Environmental Impacts... | 218 |
| A.3.1.2.3 | Health Impacts..... | 218 |
| A.3.1.3 | Summary of Long-Term Recovery... | 219 |
| A.3.1.4 | Special Aspects of the Incident | 220 |
| A.3.1.5 | Lessons Learned..... | 220 |
| A.3.2 | Anthrax Attacks in the United States (2001) .. | 221 |
| A.3.2.1 | Description of the Incident | 221 |
| A.3.2.2 | Summary of Impacts | 221 |
| A.3.2.3 | Summary of Long-Term Recovery... | 222 |
| A.3.2.4 | Special Aspects of the Incident | 223 |
| A.3.2.5 | Lessons Learned..... | 223 |
| A.3.3 | Terrorist Attacks of September 11 at New York City (2011)..... | 223 |
| A.3.3.1 | Description of the Incident | 223 |
| A.3.3.2 | Summary of Impacts | 224 |
| A.3.3.2.1 | Health Impacts..... | 224 |
| A.3.3.2.2 | Property Impacts | 225 |
| A.3.3.2.3 | Economic Impacts | 225 |
| A.3.3.2.4 | Societal Impacts..... | 225 |
| A.3.3.3 | Summary of Long-Term Recovery... | 226 |
| A.3.3.4 | Special Aspects of the Incident | 226 |
| A.3.3.5 | Lessons Learned..... | 226 |
| A.4 | Summary of Lessons Learned from Historic Incidents . | 227 |
| A.4.1 | Conclusions on Lessons Learned | 227 |

| | | |
|---|---|-----|
| A.4.2 | Resilience | 227 |
| A.4.3 | Communication | 228 |
| A.4.4 | Stakeholder Engagement | 228 |
| A.4.5 | Research and Development..... | 230 |
| A.4.6 | Pre-incident Recovery Planning..... | 230 |
| A.4.7 | Long-Term Monitoring of the Environment and Public Health | 231 |
| A.4.8 | Significance of Ongoing Lessons Learned from the Fukushima Dai-ichi Nuclear Accident..... | 231 |
| Appendix B. Current Practice in Managing Radioactive Waste 233 | | |
| B.1 | Introduction..... | 233 |
| B.2 | Waste Classification and Inherent Deficiencies | 233 |
| B.3 | Estimating Volumes of Radiological Waste and Understanding Remaining Disposal Capacities | 237 |
| B.4 | Waste Treatment and Staging | 238 |
| B.5 | Final Disposal Sites | 239 |
| B.6 | Low-Level Radioactive Waste Disposal Facilities..... | 242 |
| B.7 | Waste Transportation and Packaging | 243 |
| B.8 | Need for a Risk-Informed Radioactive Waste Management Approach..... | 243 |
| Appendix C. Decontamination Cleanup Technologies for Large Areas 245 | | |
| C.1 | Introduction..... | 245 |
| C.2 | Decontamination Technologies or Management Options for Contaminated Surfaces | 249 |
| C.2.1 | No-Action Alternative | 250 |
| C.2.2 | Biological Decontamination Technologies | 250 |
| C.2.2.1 | Microbiological Effects | 250 |
| C.2.2.2 | Phytoextraction | 251 |
| C.2.2.3 | Phytostabilization | 251 |
| C.2.3 | Chemical Decontamination Technologies or Management Options | 252 |
| C.2.3.1 | Chelation and Organic Acids | 252 |
| C.2.3.2 | Strong Mineral Acids and Related Materials | 253 |
| C.2.3.3 | Chemical Foams and Gels | 253 |
| C.2.3.4 | Oxidizing and Reducing Agents..... | 254 |
| C.2.4 | Physical Decontamination or Management Options..... | 255 |
| C.2.4.1 | Strippable Coatings | 256 |
| C.2.4.2 | Centrifugal Shot Blasting..... | 256 |
| C.2.4.3 | Concrete Grinder..... | 257 |

| | | |
|--|--|-----|
| C.2.4.4 | Concrete Shaver | 257 |
| C.2.4.5 | Concrete Spaller | 258 |
| C.2.4.6 | Dry Ice Blasting | 258 |
| C.2.4.7 | Dry Vacuum Cleaning | 258 |
| C.2.4.8 | Electro-Hydraulic Scabbling | 259 |
| C.2.4.9 | En-vac® Robotic Wall Scabbler | 259 |
| C.2.4.10 | Grit Blasting | 260 |
| C.2.4.11 | High-Pressure Water | 261 |
| C.2.4.12 | Soft Media Blast Cleaning (sponge blasting) | 261 |
| C.2.4.13 | Steam Vacuum Cleaning | 262 |
| C.2.4.14 | Piston Scabbler | 262 |
| C.3 | Decontamination Technologies or Management Options for Contaminated Media | 262 |
| C.3.1 | Decontamination Technologies or Management Options for Contaminated Soils | 263 |
| C.3.1.1 | Capping | 263 |
| C.3.1.2 | Land Encapsulation | 264 |
| C.3.1.3 | Cryogenic Barrier | 264 |
| C.3.1.4 | Vertical Barriers | 265 |
| C.3.1.5 | Cement and Chemical Solidification and/or Stabilization | 266 |
| C.3.1.6 | Solvent/Chemical Extraction | 267 |
| C.3.1.7 | Dry-Soil Separation | 268 |
| C.3.1.8 | Soil Washing | 269 |
| C.3.1.9 | Flotation | 269 |
| C.3.1.10 | <i>In Situ</i> and <i>Ex Situ</i> Vitrification | 270 |
| C.3.2 | Decontamination Technologies for Liquids | 270 |
| C.3.2.1 | Ion Exchange | 271 |
| C.3.2.2 | Chemical Precipitation | 272 |
| C.3.2.3 | Permeable Reactive Barriers | 273 |
| C.3.2.4 | Membrane Filtration | 273 |
| C.3.2.5 | Adsorption | 274 |
| C.3.2.6 | Aeration | 275 |
| C.4 | Options for Cleanup | 275 |
| Appendix D. Economic Analysis Tools | | 297 |
| D.1 | Introduction | 297 |
| D.2 | Cost-Benefit Analysis | 297 |
| D.3 | Multi-Attribute Utility Theory | 299 |
| D.4 | Computable General Equilibrium Models | 300 |
| D.5 | Pros and Cons Analysis | 302 |
| D.6 | Kepner-Tregoe Decision Analysis | 302 |
| D.7 | Analytic Hierarchy Process | 303 |

| | |
|---|-----|
| Appendix E. Risk Communication in Late-Phase Recovery from Nuclear and Radiological Incidents: Strategies, Tools and Techniques | 307 |
| E.1 Introduction..... | 307 |
| E.2 Differences Between a Nuclear or Radiological Incident and Other Hazards | 307 |
| E.2.1 Psychological and Sociological Impacts of a Radiological Incident..... | 308 |
| E.2.2 Community Support and Communication System | 309 |
| E.2.3 Messaging in the Aftermath of a Nuclear or Radiological Terrorism Incident..... | 309 |
| E.3 Strategies for Overcoming Barriers to Effective Risk Communication in Recovery from a Nuclear or Radiological Incident | 312 |
| E.3.1 Seven Cardinal Rules for Effective Risk Communication | 314 |
| E.3.2 Risk Communication Models | 317 |
| E.3.2.1 Risk Perception Model | 317 |
| E.3.2.2 Mental Noise Model | 317 |
| E.3.2.3 Negative Dominance Model | 318 |
| E.3.2.4 Trust Determination Model | 319 |
| E.3.3 Challenges to Effective Risk Communication in the Late-Phase Recovery from a Nuclear or Radiological Incident..... | 319 |
| E.3.3.1 Selectivity and Bias in Media Reporting About Risks | 319 |
| E.3.3.2 Psychological, Sociological and Cultural Factors that Create Public Misperceptions and Misunderstandings About Risks | 320 |
| E.3.4 Strategies for Overcoming Selective and Biased Reporting by the Media About Radiation Risks | 321 |
| E.3.5 Strategies for Overcoming the Psychological, Sociological, and Cultural Factors that Can Create Public Misperceptions and Misunderstandings About Risks..... | 321 |
| E.4 Summary | 348 |

| | |
|---|-----|
| Appendix F. Practical Aspects in the Optimization Process During Late-Phase Recovery | 349 |
| F.1 Characterizing Radiological Conditions | 349 |
| F.2 Environmental Contamination Considerations | 353 |
| F.2.1 Properties of Contamination in the Environment | 353 |

| | | |
|---|---|-----|
| F.2.2 | Contamination in Urban/Inhabited Areas | 355 |
| F.2.3 | Risk Characteristics of Residual Contamination | 363 |
| F.3 | Remediation Considerations | 365 |
| F.3.1 | Scope of Remediation | 365 |
| F.3.2 | Land Uses | 369 |
| F.3.3 | Decontamination | 371 |
| F.3.3.1 | Decontamination of Housing, Land and Structures | 373 |
| F.3.3.2 | Decontamination of Roads, Paved Surfaces and Gutters | 374 |
| F.3.3.3 | Decontamination of Woodland | 375 |
| F.3.3.4 | Decontamination of Farmland | 375 |
| F.3.3.5 | Volume Reduction Techniques for Waste | 375 |
| F.3.4 | Radioactive Waste | 376 |
| F.4 | Radiation Doses | 378 |
| F.4.1 | Individual Doses | 378 |
| F.4.2 | Collective Doses | 380 |
| F.4.3 | Long-Term Dose Reduction | 381 |
| F.5 | Optimization Considerations | 381 |
| F.5.1 | Multi-Attribute Approach | 381 |
| F.5.2 | Cost-Benefit Analysis | 383 |
| F.5.3 | Stakeholders Involvement in Recovery | 395 |
| F.5.3.1 | Roles and Responsibilities of Stakeholders | 396 |
| F.5.3.2 | Recovery Core Principles | 397 |
| F.5.3.3 | Recovery Success Factors | 398 |
| Appendix G. National Radiological Guidance on Late-Phase | | |
| Recovery and Related Issues | | 399 |
| G.1 | National Response Framework | 399 |
| G.2 | National Disaster Recovery Framework | 400 |
| G.3 | Federal Protective Action Guidance Specific to Nuclear or Radiological Incidents | 401 |
| G.4 | Current Statutory Cleanup Guidance and Requirements | 402 |
| Abbreviations and Acronyms | | 407 |
| Glossary | | 409 |
| References | | 427 |
| Scientific Committee and Staff | | 456 |
| The NCRP | | 466 |
| NCRP Publications | | 476 |