

CONTENTS

Preface to the Third Edition

xiii

1. Introduction to Immobilisation	1
1.1 Introduction	1
1.2 The Importance of Waste	2
1.3 Radioactive Waste	2
1.4 Recycling	4
1.5 Waste Minimisation	5
1.6 Processing and Immobilisation	6
1.7 Time Frames	6
Reference	7
Further Reading	7
2. Nuclear Decay	9
2.1 Nuclear Matter	9
2.2 Radioactive Decay	10
2.3 Decay Law	11
2.4 Radioactive Equilibrium	12
2.5 Activity	13
2.6 Alpha Decay	14
2.7 Beta Decay	15
2.8 Gamma Decay	16
2.9 Spontaneous Fission	17
2.10 Radionuclide Characteristics	18
References	22
3. Contaminants and Hazards	23
3.1 Elemental Abundance	23
3.2 Migration and Redistribution	25
3.3 Potential Hazard of Nuclear Waste	28
3.4 Relative Hazards	30
3.5 Importance of Wasteform and Real Hazard Concept	31
3.6 Wasteform Durability and Real Hazard Diminishing	32
References	34

4. Naturally Occurring Radionuclides	35
4.1 Naturally Occurring Radioactive Materials and Technologically Enhanced Naturally Occurring Radioactive Materials	35
4.2 Primordial Radionuclides	36
4.3 Use of Primordial Radionuclides for Dating	37
4.4 Natural Nuclear Reactors	38
4.5 Cosmogenic Radionuclides	39
4.6 Natural Radionuclides in Igneous Rocks	40
4.7 Natural Radionuclides in Sedimentary Rocks and Soils	41
4.8 Natural Radionuclides in Sea Water	42
4.9 Radon Emissions	42
4.10 Natural Radionuclides in the Human Body	44
References	45
5. Background Radiation	47
5.1 Radiation is Natural	47
5.2 Dose Units	48
5.3 Biological Consequences of Irradiation	49
5.4 Background Radiation	53
References	55
Further Reading	55
6. Power Utilisation of Nuclear Energy	57
6.1 Nuclear Energy Sources	57
6.2 Geothermal Energy	59
6.3 Radioisotope Thermoelectric Generators	59
6.4 Power Nuclear Reactors	61
6.5 Nuclear Fuel Cycle	66
References	69
7. Non-Power Use of Nuclear Energy	71
7.1 Non-Power Applications	71
7.2 Scientific Applications	71
7.3 Medical and Biological Applications	73
7.4 Industrial Applications	74
7.5 Food Processing and Agriculture	78
References	79

8. Nuclear Waste Regulations	81
8.1 Regulatory Organisations	81
8.2 Protection Philosophies	82
8.3 Regulation of Radioactive Materials and Sources	83
8.4 Exemption Criteria and Levels	84
8.5 Discharges	86
8.6 Clearance of Materials From Regulatory Control: Moderate Amounts	86
8.7 Clearance of Materials From Regulatory Control: Bulk Amounts	89
8.8 Conditional Clearance	91
8.9 Double Standards	92
8.10 Dose Limits	93
8.11 Control of Radiation Hazards	93
8.12 Nuclear Waste Classification	95
8.13 International Atomic Energy Agency Classification Scheme	96
8.14 Examples of Waste Classification	99
8.15 Radioactive Waste Regulations and International Atomic Energy Agency Standards	102
References	105
Further Reading	106
9. Principles of Nuclear Waste Management	107
9.1 International Consensus	107
9.2 Objective of Radioactive Waste Management	108
9.3 Fundamental Principles	108
9.4 Comments on the Fundamental Principles	110
9.5 Fundamental Safety Principles	116
9.6 Ethical Principles	116
9.7 Joint Convention	117
9.8 International Cooperation	118
References	118
10. Nuclear Waste Types and Sources	119
10.1 Sources of Nuclear Waste	119
10.2 Front-End and Operational Nuclear Fuel Cycle Waste	122
10.3 Open Nuclear Fuel Cycle Back-End Radioactive Waste	125
10.4 Closed Nuclear Fuel Cycle Back-End Radioactive Waste	128
10.5 Back-End Nuclear Fuel Cycle Decommissioning Waste	130
10.6 Non-Nuclear Fuel Cycle Wastes	132
10.7 Accidental Wastes	137

10.8 Global Inventory	142	14.3 Sampling and Characterisation of Surface Contamination	195
References	142	14.4 Waste Characterisation Techniques	199
11. Short-Lived Waste Radionuclides	145	14.5 Characterisation of Waste Packages and Wasteforms	206
11.1 Introduction	145	14.6 Characterisation of Environment and Personnel	212
11.2 Tritium	146	14.7 Characterisation of Materials for Clearance	214
11.3 Cobalt-60	148	Further Reading	215
11.4 Strontium-90	149	15. Pre-Treatment of Radioactive Wastes	217
11.5 Caesium-137	152	15.1 Pre-Treatment Objectives	217
References	154	15.2 Collection and Segregation	218
12. Long-Lived Waste Radionuclides	155	15.3 Adjustment	219
12.1 Introduction	155	15.4 Size Reduction	220
12.2 Carbon-14	155	15.5 Packaging	222
12.3 Technetium-99	158	15.6 Decontamination	223
12.4 Iodine-129	160	References	230
12.5 Plutonium	161	16. Treatment of Radioactive Wastes	231
12.6 Neptunium-237	163	16.1 Treatment Objectives	231
12.7 Nuclear Criticality	164	16.2 Treatment of Aqueous Wastes	232
References	165	16.3 Treatment of Organic Liquid Wastes	246
13. Nuclear Waste Processing Schemes	167	16.4 Treatment of Solid Wastes	248
13.1 Nuclear Waste Management Roadmap	167	16.5 Treatment of Gaseous and Airborne Effluents	261
13.2 Waste Lifecycle	168	16.6 Partitioning and Transmutation	267
13.3 Predisposal	170	References	268
13.4 Disposal	172	17. Immobilisation of Radioactive Waste in Cement	271
13.5 Categorisation for Processing	174	17.1 Wasteforms	271
13.6 Selection of Processing Technologies	177	17.2 Cementitious Wasteforms	272
13.7 Wasteforms	183	17.3 Hydraulic Cements	273
13.8 Waste Packages	187	17.4 Cement Hydration	276
13.9 Processing of Naturally Occurring Radioactive Material Waste	188	17.5 Phase Composition of Hydrated Cements	282
13.10 <i>In Situ</i> Decommissioning	189	17.6 Cementation of Radioactive Wastes	283
References	189	17.7 Modified and Composite Cement Systems	284
Further Reading	190	17.8 Alternative Cementitious Systems	287
14. Characterisation of Radioactive Waste	191	17.9 Cementation Technology	296
14.1 Approaches to Waste Characterisation	191	17.10 Acceptance Criteria	299
14.2 Characterisation of Radiation Fields	192	References	302

18. Immobilisation of Radioactive Waste in Bitumen	305		
18.1 Bituminisation	305		
18.2 Composition and Properties of Bitumen	306		
18.3 Bituminous Materials for Waste Immobilisation	307		
18.4 Waste Loading	309		
18.5 Bituminisation Technique	310		
18.6 Acceptance Criteria	313		
18.7 Bitumen Versus Cement	314		
18.8 Immobilisation of Radioactive Waste in Polymers	317		
References	318		
19. Immobilisation of Radioactive Wastes in Glass	319		
19.1 The Vitreous State	319		
19.2 Glasses for Nuclear Waste Immobilisation	323		
19.3 Immobilisation Mechanisms	327		
19.4 Borosilicate Glasses	328		
19.5 Cations in Silicate Glasses	331		
19.6 Degree of Polymerisation	332		
19.7 Role of Boron Oxide	334		
19.8 Role of Intermediates and Modifiers	335		
19.9 Difficult Elements	336		
19.10 Selection Rules for a Nuclear Wasteform Silicate Glass	338		
19.11 Phosphate Glasses	339		
19.12 Glass Composite Materials	341		
19.13 Vitrification Technology	342		
19.14 Development of Vitrification Technologies	346		
19.15 Calcination Processes	356		
19.16 Cold Crucible Melters	360		
19.17 <i>In Situ</i> Vitrification	363		
19.18 Radionuclide Volatility	365		
19.19 Wasteform Acceptance Criteria	366		
References	367		
Further Reading	368		
20. Ceramics and Novel Technologies	369		
20.1 New Approaches to Waste Immobilisation	369		
20.2 Crystalline Wasteforms	371		
20.3 Actinide-Hosting Ceramics	375		
20.4 Polyphase Crystalline Wasteforms: Synroc	377		
		20.5 Polyphase Wasteforms: Glass-Crystalline Composites	379
		20.6 New Technological Approaches	382
		20.7 Metal Matrix Immobilisation	391
		References	394
		21. Transport and Storage of Radioactive Waste	397
		21.1 Transportation	397
		21.2 Storage	402
		21.3 Spent Nuclear Fuel Storage	409
		21.4 Spent Nuclear Fuel Behaviour in Interim Storage	410
		21.5 Storage Inventory	412
		References	412
		Further Reading	413
		22. Nuclear Waste Disposal	415
		22.1 Disposal/Storage Concepts	415
		22.2 Retention Times	416
		22.3 Multi-Barrier Concept	417
		22.4 Disposal/Storage Options	418
		22.5 Role of the Engineered Barrier System	423
		22.6 Importance of Natural Geological Barrier	425
		22.7 Transport of Radionuclides	427
		22.8 Disposal Experience	429
		22.9 Acceptance Criteria	431
		References	432
		Further Reading	432
		23. Performance of Wasteform Materials	433
		23.1 Cementitious Materials Performance	433
		23.2 Bitumen Performance	439
		23.3 Glass Performance	440
		23.4 Glass Corrosion Mechanisms	441
		23.5 Glass Performance in Confined Conditions of a Geological Repository	446
		23.6 Radiation Effects in Glasses	449
		23.7 Radiation Damage in Crystalline Wasteforms	452
		23.8 Spent Nuclear Fuel Behaviour in Geological Disposal	456
		23.9 Research Laboratories	458
		References	460
		Further Reading	461

24. Safety Assessments	463
24.1 International Standards for Safety Case and Safety Assessment	463
24.2 Safety Case	464
24.3 Safety Requirements	465
24.4 Safety Assessment Report	467
24.5 Safety Assessment Process	469
24.6 Safety Assessment Software Tools	471
References	474
25. Conclusion	475
Further Reading	475
<i>Index</i>	477