

CONTENTS

PREFACE	xiii
---------	------

Chapter 1 Review of the Nuclear Fuel Cycle

1.1	General Comments	1
1.2	Nuclear Fission Reactor Types	3
1.3	Generations of Fission Reactors	3
1.4	GEN-II Reactors	6
1.5	GEN-III Reactors	10
1.6	Small Modular Reactors (SMRs)	16
1.7	Nuclear Fuel Activities	19
1.8	Nuclear Fuel Cycles	22
1.9	Glossary of Nuclear Fuel Terms	24
	Bibliography	26
	General Websites	26

Chapter 2 Nuclear Fuel Resources, Mining, and Milling

2.1	Introduction	28
2.2	Uranium Exploration Techniques	29
2.2.1	Geological Studies	29
2.2.2	Airborne Surveys	30
2.2.3	Surface Surveys	32
2.2.4	Hydrochemical Methods	33
2.2.5	Well Logging	34
2.2.6	Botanical Methods	35
2.3	Principal Uranium-Bearing Minerals	35
2.4	Uranium Mining Methods	35
2.4.1	Open-Pit Mining	36
2.4.2	Underground Mining	37

2.4.3	<i>In Situ</i> Leaching (Solution Mining)	37
2.4.4	Recovery of Uranium as By-Product from Mining Other Materials	38
2.4.5	Recovery of Uranium from Seawater	39
2.5	Uranium Exploration and Mine Activities	40
2.6	The Milling of Uranium Ore	42
2.7	The Mill Tailings	42
2.8	Uranium Reserves and Resources	47
2.9	Uranium Production	49
2.10	Economic Considerations of Uranium Production Methods	50
2.11	Thorium Minerals and Estimated Reserves	51
	Bibliography	54
	References	54
	Problems	55

Chapter 3 Conversion and Enrichment

3.1	Introduction	57
3.2	Purification of U_3O_8	58
3.3	Conversion of U_3O_8 to UF_6	58
3.4	Enrichment of Uranium by Gaseous Diffusion	62
3.5	Quantitative Aspects of Enrichment by Gaseous Diffusion	65
3.6	The Management of Uranium Enrichment Tails	70
3.7	The United States Enrichment Corporation (USEC)	71
3.8	The Use of Weapons Uranium for Civilian Nuclear Fuel	71
3.9	Enrichment of Uranium by the Centrifuge Method	72
3.10	Enrichment of Uranium by the Separation Nozzle Method	75
3.11	Enrichment of Uranium Using Lasers	76
3.12	Enrichment Prices and Contracts	79
3.13	World Enrichment Capacity	81
	Bibliography	82
	General Websites	82
	References	82
	Problems	83

Chapter 4 Fuel Design and Fabrication

4.1	Introduction	86
4.2	Reactor Fuel and Cladding Materials	88
4.2.1	Uranium Metal	88
4.2.2	Ceramic Fuels	88
4.2.3	Fuel Cladding	91
4.2.4	Burnable Absorbers or Burnable Poisons	93
4.3	Fuel Element Fabrication	95
4.3.1	Fuel Pellet Production	95

4.3.2	Fuel Rod Loading	98
4.3.3	Fuel Assembly for a PWR	99
4.3.4	Fuel Assembly for a BWR	102
4.3.5	Fuel Assembly Identification Scheme	102
4.4	LWR Fuel Problems and Solutions	104
4.4.1	Nuclear Fuel Problems	104
4.4.2	Barrier Fuel	108
4.4.3	VANTAGE-5 Fuel	109
4.5	Examination of Irradiated Fuel for Defects: Fuel Sipping	109
4.6	Axial and Radial Blankets	110
4.7	Other Types of Power Reactor Fuels	111
4.7.1	The Gas-Cooled GT-MHR and Pebble Bed Reactor Fuel	111
4.7.2	The MOX Fuel	113
4.7.3	Future Fuel Designs	114
4.8	Fuel Fabrication Cost	115
4.9	Materials Concerns Relative to Plant Life Extension	116
	Bibliography	116
	References	117
	Problems	119

Chapter 5 Reactor Physics Calculations

5.1	Introduction	120
5.2	The Neutron Transport Equation	122
5.2.1	General Comments and Derivation of the Transport Equation	122
5.2.2	The Diffusion Approximation	125
5.2.3	The Multigroup Diffusion Approximation Formalism	126
5.2.4	Criticality Calculation Using the Multigroup Equations	131
5.2.5	One- and Two-Group Diffusion Equation Calculations	134
5.2.6	Numerical Solution of the Multigroup Equations	137
5.2.7	The Transport Approximations P_N and S_N	140
5.2.8	Nodal Methods	143
5.2.9	The Monte Carlo Method	145
5.3	Nuclear Cross-Section Data	150
5.3.1	The ENDF/B Library	150
5.3.2	Information Provided by ENDF/B	151
5.3.3	Calculation of the Neutron Energy Spectrum $\phi(E)$	152
5.3.4	Cross-Section Libraries for Multigroup Calculations	156
5.4	Fundamentals of Core Reload Calculations	158
5.4.1	Objectives of Reload Calculations	158
5.4.2	Calculation of the Average Power per Assembly	160
5.5	Fuel Depletion Calculations	163
5.6	Burnable Poison Calculations—Chemical Shim	167

5.7	Control Rod Calculations	172
	Bibliography	178
	References	179
	Problems	182

Chapter 6 In-Core Fuel Management

6.1	General Comments	185
6.2	Multibatch Core Loading	188
6.2.1	Burnup, Capacity, and Availability Factors	189
6.2.2	The Reactivity of the Core	190
6.2.3	One- and Two-Batch Cores	192
6.2.4	The <i>N</i> -Batch Core	195
6.3	Fuel Loading Patterns	196
6.3.1	OUT-IN Loading	199
6.3.2	Scatter Loading	200
6.3.3	Low-Leakage Core Loading	201
6.3.4	Gas-Cooled Reactor Fuel Loading	205
6.4	Extended Burnup and Longer Fuel Cycle Length	207
6.4.1	Effect of Extended Burnup on Fuel Performance	207
6.4.2	Effect of Extended Burnup on Uranium and Enrichment Needs	208
6.4.3	Other Effects Due to Higher Burnup	208
6.4.4	Effects Due to Fuel Cycle Length	208
6.4.5	The Effect of NWPA on Extended Burnup	211
6.4.6	Fuel Cycle Stretchout (Coastdown)	213
6.5	Burnup Measurement Techniques	214
6.6	Refueling Activities	215
6.6.1	Planning for a Refueling Outage	216
6.6.2	Reload Fuel Procurement	218
6.6.3	Reload Fuel Design Activities	219
6.6.4	Licensing the Reload Fuel	220
6.6.5	Refueling Outage Tasks	221
6.6.6	Maintenance Activities	223
6.7	Radiation Exposure to Personnel	224
	Bibliography	226
	References	226
	Problems	230

Chapter 7 Reprocessing and Recycling

7.1	What Is Reprocessing and Recycling?	232
7.2	An Historical Perspective	232
7.3	Why Consider Reprocessing and Recycling?	235

7.4	Reprocessing	238
7.4.1	General Comments	238
7.4.2	The PUREX Method of Reprocessing	239
7.4.3	The Pyrometallurgical Method of Reprocessing	240
7.4.4	Proliferation-Resistant Processes	240
7.4.5	Materials Accountability of Reprocessing Plants	241
7.4.6	Reprocessing Experience in the United States	242
7.4.7	Reprocessing Experience Outside the United States	243
7.5	Plutonium and Uranium Recycling in LWRs	244
7.5.1	Materials Flow with Recycling	244
7.5.2	Natural Uranium Savings Due to U and Pu Recycling	245
7.5.3	SWU Savings Due to U and Pu Recycling	249
7.6	Characteristics of a Reactor Core with MOX Fuel	250
7.7	Problems with Recycled Uranium	253
7.8	Problems with Recycled Plutonium	254
7.9	Experience with MOX Fuel Used in LWRs	256
7.10	Recycling/Burning of Minor Actinides	258
7.11	Factors Affecting Implementation of Reprocessing and Recycling	259
	Bibliography	261
	References	261
	Problems	264

Chapter 8 Electric Utility and Nuclear Power Economics

8.1	General Comments and Definitions	266
8.1.1	Capital and Business Activities	266
8.1.2	The Engineer's Role in Business	266
8.1.3	Financial Terms	267
8.1.4	Business Taxes	268
8.1.5	Depreciation	269
8.1.6	The Time Value or the Present Worth of Money	271
8.2	The Electric Utility as a Business	275
8.2.1	Main Financial Characteristics of Utilities	275
8.2.2	The Cash Flow Statement	276
8.2.3	The Electric Utility Regulatory System	277
8.2.4	The Effects of Load Demand Variation	279
8.3	The Special Features of Nuclear Fuel	280
8.3.1	Nuclear and Fossil Fuels	280
8.3.2	The Investment in Nuclear Fuel as a Function of Time	281
8.3.3	Leasing or Buying Nuclear Fuel	281
8.4	Cost Components for Nuclear Electricity Generation	282
8.4.1	Plant Construction	282
8.4.2	Operation and Maintenance	283

8.4.3	Fuel	283
8.4.4	Taxes	285
8.4.5	Regulations	285
8.5	Calculation of the Cost of Electricity	285
8.5.1	An Approximate Calculation	285
8.5.2	The Levelized Cost of Electricity	286
8.5.3	Comments on the Equation for the Levelized Cost	291
8.5.4	The Levelized Cost over a Period of Time	295
8.6	Comparison of Electricity Generation Costs from Various Plants	296
	Bibliography	298
	General Websites	298
	References	298
	Problems	299

Chapter 9 High-Level Waste Management

9.1	General Comments	302
9.2	Classification of Radioactive Wastes	306
9.3	Sources and Examples of Radioactive Wastes	307
9.4	HLW Management Policy Acts	307
9.4.1	The Nuclear Waste Policy Act (NWPA) of 1982 and Its 1987 Amendments	307
9.4.2	The Blue Ribbon Commission (BRC) of 2010	312
9.4.3	European Policy	314
9.4.4	Russian Policy	315
9.4.5	Other Countries' Policies	315
9.5	Used Nuclear Fuel Management	316
9.5.1	UNF Storage	316
9.5.2	Burnup Credit	323
9.5.3	Radioactivity from UNF	323
9.5.4	Decay Heat Generated by UNF	326
9.5.5	UNF Management Outside the United States	334
9.6	Disposal of HLW and TRU Wastes	335
9.6.1	Characteristics of HLW	335
9.6.2	Characteristics of TRU	337
9.6.3	Solidification of Liquid HLW	340
9.6.4	Disposal Methods	345
9.6.5	The Form of the Waste for Disposal: Transmutation	347
9.6.6	Geologic Repository Features	348
9.6.7	The Waste Isolation Pilot Plant	352
9.6.8	HLW Disposal Programs Outside the United States	353
9.7	Transportation of Radioactive Materials	355
9.7.1	Transportation Regulations	355
9.7.2	Definitions and Classifications	356

9.7.3	Shipper–Recipient Responsibilities	361
9.7.4	Testing of Shipping Casks for UNF	361
9.8	Emergency Preparedness: Response to Accidents	364
	Bibliography	365
	General Websites	366
	References	366
	Problems	372

Chapter 10 LLW Management and Decommissioning of Nuclear Facilities

10.1	Sources of LLW	374
10.2	The LLW Policy Act of 1980 and Its 1985 Amendments	374
10.2.1	The LLW Compacts	377
10.3	Disposal of LLW	379
10.3.1	Characteristics of LLW	379
10.3.2	Classification of LLW into A, B, C, and GTCC Classes	379
10.3.3	Disposal Requirements for Class A, B, C, and GTCC Wastes	383
10.3.4	Volume Reduction Methods	384
10.3.5	Solidification of LLW	384
10.3.6	LLW Disposal Sites	385
10.3.7	LLW Disposal Programs Outside the United States	386
10.4	Decommissioning of Nuclear Facilities	388
10.4.1	What Is Decommissioning?	388
10.4.2	Decommissioning Methods	390
10.4.3	Radioactive Materials Involved in Decommissioning	391
10.4.4	Decontamination Methods	392
10.4.5	Financing and Cost of Decommissioning	393
10.4.6	Decommissioning Experience	395
10.5	Transportation of LLW	397
	Bibliography	399
	References	399
	Problems	401

Chapter 11 Nuclear Nonproliferation and Safeguards

11.1	What Is Nuclear Nonproliferation and Safeguards?	402
11.2	The Role of the International Atomic Energy Agency	403
11.3	The Non-Proliferation Treaty	404
11.3.1	Information Circulars	407
11.4	Safeguards	408
11.4.1	Compliance with Safeguards	408
11.4.2	Noncompliance with Safeguards	410
11.5	Strategic Nuclear Materials—IAEA Definitions	411

11.6	Nuclear Fuel Cycles and Proliferation	412
11.7	Detection of Nuclear Materials	413
	11.7.1 Passive Detection Methods	413
	11.7.2 Active Detection Methods	414
11.8	Proliferation Resistance and Physical Protection	415
11.9	Concluding Remarks	417
	Bibliography	417
	References	418

Chapter 12 Environmental Effects from the Generation of Electricity

12.1	Introduction	420
12.2	The Various Types of Electricity Generating Systems and Their Environmental Effects	422
12.3	External Costs of Energy Production	423
12.4	Fossil-Fueled Plants	423
	12.4.1 The Greenhouse Effect and Climate Change	425
	12.4.2 Acid Rain	429
12.5	Hydroelectric Power Plants	430
12.6	Geothermal Power Plants	432
12.7	Solar Power Plants	433
12.8	Wind Power Plants (Wind Farms)	434
12.9	Less Developed Electric Power Plants	435
12.10	Nuclear Power Plants and Their Environmental Effects	437
12.11	Comparison of the Various Energy Systems	443
12.12	Summary and Conclusions	445
	Bibliography	450
	References	451

INDEX	453
-------	-----

ABOUT THE AUTHOR	463
------------------	-----