

Contents

CHAPTER 1. SURVEY OF NUCLEAR POWER SYSTEMS	1
1-1. Introduction	1
1-2. Nuclear Energy Conversion	1
1-3. Energy from Nuclear Fusion	5
1-4. The Fusion Reactor	6
1-5. Energy from Nuclear Fission	7
1-6. The Chain Reaction	9
1-7. Neutron Energies and Moderation	9
1-8. Conversion and Breeding	11
1-9. Fission Power Plants	12
1-10. Direct Conversion of Nuclear Energy	19
CHAPTER 2. SOME THERMODYNAMIC ASPECTS OF NUCLEAR POWER	22
2-1. Introduction	22
2-2. The Carnot Cycle and Efficiency	24
2-3. Actual Cycles and the Concept of Reversibility	27
2-4. The Rankine Cycle	29
2-5. The Efficiency and Work of a Nuclear Plant Operating on an Irreversible Cycle	31
2-6. Regeneration	35
2-7. Heat Addition with a Variable-Temperature Heat Source . .	38
2-8. Superheat and Reheat Cycles	43
2-9. The Choice of Working Fluid	45
2-10. Multifluid Vapor Cycles	47
Problems	55
CHAPTER 3. THE BOILING REACTOR	58
3-1. Introduction	58
3-2. Boiling Reactor Mass and Heat Balance	60
3-3. The Driving Pressure in a Boiling Channel	62
3-4. The Average Density in a Boiling Channel	66
3-5. The Chimney Effect	70
3-6. The Multichannel Boiling Core	72

Contents

3-7.	The Void Coefficient in Water Reactors	78
3-8.	The Case of Ordinary-Water Reactors with Highly Enriched Fuels	79
3-9.	The Case of Ordinary-Water Reactors with Low-Enriched Fuels	83
3-10.	The Case of Heavy-Water Reactors	85
3-11.	Pressure Coefficients in Boiling Reactors	85
3-12.	Boiling-Water-Reactor Stability Problems	88 90
CHAPTER 4. BOILING-REACTOR POWER PLANTS		94
4-1.	Introduction	94
4-2.	Radioactivity of the Steam System	95
4-3.	The Direct Cycle Power Plant	96
4-4.	The Experimental Boiling-Water Reactor (EBWR)	98
4-5.	The Dual-Cycle Power Plant	104
4-6.	The Dresden I Nuclear Power Plant	107
4-7.	Plant Control by Recirculation Flow	112
4-8.	The Browns Ferry Nuclear Power Station	113
4-9.	The Pathfinder Boiling Reactor	125
4-10.	A Graphite-Water Boiling Superheat Reactor	130
4-11.	The Variable Moderator Boiling Reactor (VMR)	133
4-12.	Boiling-Water-Reactor Turbines Problems	139 143
CHAPTER 5. PRESSURIZED-WATER REACTORS		145
5-1.	Introduction	145
5-2.	Materials for Water Reactors	146
5-3.	Steam Generators	149
5-4.	Reactor-System Pressurizers	151
5-5.	Chemical Shim Control	156
5-6.	Pressurized Heavy-Water Reactors Problems	162 165
CHAPTER 6. PRESSURIZED-WATER REACTOR POWER PLANTS		167
6-1.	Introduction	167
6-2.	The Shippingport Atomic Power Station	169
6-3.	The Indian Point I Reactor Power Plant	172
6-4.	The Point Beach Reactor Power Plant	173
6-5.	The Pickering Heavy-Water Reactor Power Plant	182
6-6.	The Fluidized-Bed Concept	185
6-7.	The Fluidized-Bed Reactor Problems	191 194

Contents

CHAPTER 7. GAS-COOLED REACTORS	196
7-1. Introduction	196
7-2. Thermodynamic Cycles	197
7-3. Gas-Coolant Radioactivity	200
7-4. Comparison of Gas Coolants on the Basis of Heat Transfer and Pumping Power	203
7-5. Thermodynamic Comparison of Gas Coolants in Direct-Cycle Applications	207
7-6. The Actual Cycle	212
7-7. Other Comparisons of Gaseous Coolants	217
7-8. The Effect of Fuel-Element Type on Gas-Cooled-Reactor Design	220
Problems	224
CHAPTER 8. GAS-COOLED REACTOR POWER PLANTS	226
8-1. Introduction	226
8-2. Analysis of the Gas-Steam System: The Simple Cycle	226
8-3. Analysis of the Gas-Steam System: The Dual-Pressure Cycle	233
8-4. The U.K. Gas-Cooled Reactor Program	237
8-5. The Hinkley Point A Station	239
8-6. The Hinkley Point B Station	243
8-7. The High-Temperature Gas-Cooled Reactor (HTGR)	248
8-8. The Peach Bottom HTGR Plant	250
8-9. The Fort Saint Vrain HTGR	254
8-10. The Large HTGR	259
8-11. Pebble-Bed Reactors	266
8-12. The Arbeitsgemeinschaft Versuchsreaktor (AVR)	271
8-13. The Thorium High-Temperature Reactor (THTR)	274
8-14. A Gas-Cooled Mobile Low-Power Reactor	277
8-15. Other Gas-Cooled Reactor Concepts	278
Problems	278
CHAPTER 9. THE FAST BREEDER REACTOR	280
9-1. Introduction	280
9-2. Nuclear Reactions in Fast-Breeder Reactors	281
9-3. Conversion and Breeding	284
9-4. The Conversion (Breeding) Ratio	286
9-5. Doubling Time	289
9-6. Some Safety Aspects of Fast Reactors	291
9-7. Fast-Reactor Kinetics	293

Contents

9-8.	The Sodium Void Coefficient	295
9-9.	The Doppler Effect in Fast Reactors	298
9-10.	Flux Distributions in Fast Reactors	299
9-11.	Fast-Reactor Coolants, Liquid Metals	303
9-12.	Fast-Reactor Coolants, Gases and Steam	307
9-13.	Material Swelling in Fast Reactors	309
9-14.	The Impetus for Fast Reactors	311
	Problems	312

CHAPTER 10. FAST-BREEDER REACTORS AND POWER PLANTS . . . 313

10-1.	Introduction	313
10-2.	Reactor-Plant Arrangements	315
10-3.	The Enrico Fermi Nuclear Power Plant	317
10-4.	Large Sodium-Cooled Fast Reactors	319
10-5.	The Clinch River Breeder Reactor Project	323
10-6.	The Super Phénix LMFBR	340
10-7.	The Gas-Cooled Fast Breeder Reactor	354
10-8.	The Steam-Cooled Fast Reactor	359

CHAPTER 11. FLUID-FUELED REACTORS AND POWER PLANTS . . . 363

11-1.	Introduction	363
11-2.	Advantages and Disadvantages	364
11-3.	Fluid-Fueled-Reactor Types	365
11-4.	Corrosion and Erosion Characteristics of Fluid Fuels	368
11-5.	Reactor-Vessel Design	369
11-6.	Some Aqueous-Fuel Reactors	371
11-7.	Liquid-Metal-Fuel Reactors	376
11-8.	Molten-Salt Reactors	379

CHAPTER 12. ORGANIC-COOLED AND MODERATED REACTORS . . . 390

12-1.	Introduction	390
12-2.	Organic Liquids for Reactors	391
12-3.	Radiolytic and Pyrolytic Damage to Organic Coolants	394
12-4.	Induced Radioactivity in Organic Coolants	400
12-5.	Other Characteristics of Organic Coolants	401
12-6.	Heat Transfer of Polyphenyl Coolants	401
12-7.	Polyphenyl Cleanup and Operating Costs	405
12-8.	Some Other Characteristics of Organic-Cooled Reactors	407
12-9.	The Organic Moderated Reactor Experiment (OMRE)	410
12-10.	The Piqua OMR Power Plant	413

Contents

CHAPTER 13. THERMIONIC ENERGY CONVERSION 417

13-1.	Introduction	417
13-2.	Components of a Thermionic Converter	418
13-3.	Solid Phenomena	419
13-4.	Surface Phenomena	422
13-5.	Space Phenomena	425
13-6.	The Vacuum Diode	426
13-7.	Efficiency of a Vacuum Diode	429
13-8.	The Plasma Diode	434
13-9.	Plasma-Diode Characteristics	436
13-10.	Heat Sources for Thermionic Converters	440
13-11.	The In-Pile Thermionic Converter	443
13-12.	Some Thermionic Studies	447
13-13.	A Small Thermionic Diode	450
	Problems	453

CHAPTER 14. THERMOELECTRIC ENERGY CONVERSION 455

14-1.	Introduction	455
14-2.	The Band Theory of Solids	456
14-3.	Semiconductors	459
14-4.	Thermoelectric Effects	460
14-5.	Thermoelectric Conversion Principles	464
14-6.	Converter-Performance Parameters	466
14-7.	Converter Efficiency Optimization	470
14-8.	Converter Power Optimization	478
14-9.	Thermoelectric Materials	479
14-10.	Thermopiles, Cascaded and Segmented Converters	483
14-11.	The SNAP 10A System	486
14-12.	Second-Generation Systems	492
14-13.	Isotopic Power Devices	494
14-14.	SNAP-27	496
	Problems	498

CHAPTER 15. DIRECT ENERGY CONVERSION OF NUCLEAR RADIATIONS 500

15-1.	Introduction	500
15-2.	Nuclear Radiation Converter Types	500
15-3.	The Betavoltaic Cell	501
15-4.	Betavoltaic Batteries	506
15-5.	The Fission Electric Cell	509
15-6.	Performance Parameters of an FEC	511
15-7.	Some Practical FECs	514
	Problems	516

Contents

CHAPTER 16. FUSION POWER 518

16-1.	Introduction	518
16-2.	Fusile Fuel and Reactions	519
16-3.	The Plasma	520
16-4.	Plasma Temperatures	522
16-5.	Plasma Heating and Injection	526
16-6.	Plasma Confinement	528
16-7.	Magnetic Pinch Confinement	531
16-8.	Confinement by Open-Ended or Magnetic Mirror Machines	535
16-9.	Confinement in Closed-Geometry or Stellarator Machines	536
16-10.	Other Confinement Schemes	540
16-11.	Plasma Density and Confinement Time	542
16-12.	The D-T Fusion Reactor Power Plant	546
16-13.	Tritium-Breeding and Neutron Multiplication	548
16-14.	Some Technological Problems	551
16-15.	A Direct-Conversion Fusion Power Plant	553
16-16.	The Fusion Torch	556
	Problems	557

CHAPTER 17. NUCLEAR POWER ECONOMICS 559

17-1.	Introduction	559
17-2.	Nuclear Power Costs	560
17-3.	Direct Capital Costs	563
17-4.	Indirect Capital Costs	566
17-5.	Fixed Charges	569
17-6.	The Fuel Cycle	572
17-7.	Fuel-Cycle Costs	578
17-8.	Computational Techniques of the Fuel Cycle	581
17-9.	Operation and Maintenance Costs	583
17-10.	Some Basic Definitions	585
17-11.	Computation of Power Costs	587
	Problems	591

Appendix A Alphabetical List of the Elements 595

Appendix B Some Thermodynamic Properties 597

Appendix C Some Physical Properties 625

Appendix D Moody Friction Factor Chart 629

Appendix E Some Useful Constants 631

Appendix F Some Conversion Factors 633

REFERENCES 641

INDEX 653