

Contents

<i>Preface</i>	<i>page</i> ix
<i>Mathematical Nomenclature</i>	xi
1 Introduction	1
1.1 Background and Context	1
1.2 This Book	2
2 Basic Nuclear Power Generation	5
2.1 Nuclear Power	5
2.2 Nuclear Fuel Cycle	5
2.2.1 Thorium Fuel Cycle	7
2.2.2 Fuel Changes in the Reactor	8
2.2.3 The Postreactor Stages	8
2.3 Nuclear Physics	9
2.3.1 Basic Nuclear Fission	9
2.3.2 Neutron Energy Spectrum	10
2.3.3 Cross Sections and Mean Free Paths	11
2.3.4 Delayed Neutrons and Emissions	13
2.4 Radioactivity and Radioactive Decay	13
2.4.1 Half-Life	13
2.4.2 Decay in a Nuclear Reactor	14
2.5 Radiation	15
2.6 Containment Systems	16
2.6.1 Radioactive Release	16
2.6.2 Reactor Shielding	17
2.7 Natural Uranium Reactors	18
2.8 Thermal Reactors	18
2.8.1 Moderator	18
2.8.2 Neutron History in a Thermal Reactor	20

2.9	Fast Reactors	21
2.10	Criticality	21
2.11	Fuel Cycle Variations	22
3	Core Neutronics	25
3.1	Introduction	25
3.2	Neutron Density and Neutron Flux	25
3.3	Discretizing the Energy or Speed Range	26
3.4	Averaging over Material Components	27
3.5	Neutron Transport Theory	28
3.6	Diffusion Theory	30
3.6.1	Introduction	30
3.6.2	One-Speed and Two-Speed Approximations	32
3.6.3	Steady State One-Speed Diffusion Theory	33
3.6.4	Two-Speed Diffusion Theory	34
3.6.5	Nonisotropic Neutron Flux Treatments	36
3.6.6	Multigroup Diffusion Theories and Calculations	36
3.6.7	Lattice Cell Calculations	37
3.7	Simple Solutions to the Diffusion Equation	37
3.7.1	Spherical and Cylindrical Reactors	37
3.7.2	Effect of a Reflector on a Spherical Reactor	40
3.7.3	Effect of a Reflector on a Cylindrical Reactor	42
3.7.4	Effect of Control Rod Insertion	43
3.8	Steady State Lattice Calculations	45
3.8.1	Introduction	45
3.8.2	Fuel Rod Lattice Cell	47
3.8.3	Control Rod Lattice Cell	49
3.8.4	Other Lattice Scales	50
3.9	Unsteady or Quasi-Steady Neutronics	51
3.9.1	Unsteady One-Speed Diffusion Theory	51
3.9.2	Point Kinetics Model	53
3.10	More Advanced Neutronic Theory	53
3.11	Monte Carlo Calculations	54
4	Some Reactor Designs	56
4.1	Introduction	56
4.2	Current Nuclear Reactors	56
4.3	Light Water Reactors (LWRs)	57
4.3.1	Types of LWRs	57
4.3.2	Pressurized Water Reactors (PWRs)	58
4.3.3	Boiling Water Reactors (BWRs)	60
4.3.4	Fuel and Control Rods for LWRs	62
4.3.5	Small Modular Reactors	65
4.3.6	LWR Control	66

<i>Contents</i>	vii
4.4 Heavy Water Reactors (HWRs)	67
4.5 Graphite-Moderated Reactors	69
4.6 Gas-Cooled Reactors	69
4.7 Fast Neutron Reactors (FNRs)	70
4.8 Liquid Metal Fast Breeder Reactors	70
4.9 Generation IV Reactors	74
4.9.1 Generation IV Thermal Reactors	75
4.9.2 Generation IV Fast Reactors	76
5 Core Heat Transfer	78
5.1 Heat Production in a Nuclear Reactor	78
5.1.1 Introduction	78
5.1.2 Heat Source	78
5.1.3 Fuel Rod Heat Transfer	79
5.1.4 Heat Transfer to the Coolant	82
5.2 Core Temperature Distributions	83
5.3 Core Design: An Illustrative LWR Example	84
5.4 Core Design: An LMFBR Example	85
5.5 Boiling Water Reactor	86
5.5.1 Temperature Distribution	86
5.5.2 Mass Quality and Void Fraction Distribution	87
5.6 Critical Heat Flux	89
6 Multiphase Flow	90
6.1 Introduction	90
6.2 Multiphase Flow Regimes	90
6.2.1 Multiphase Flow Notation	90
6.2.2 Multiphase Flow Patterns	91
6.2.3 Flow Regime Maps	92
6.2.4 Flow Pattern Classifications	93
6.2.5 Limits of Disperse Flow Regimes	95
6.2.6 Limits on Separated Flow	96
6.3 Pressure Drop	99
6.3.1 Introduction	99
6.3.2 Horizontal Disperse Flow	99
6.3.3 Homogeneous Flow Friction	100
6.3.4 Frictional Loss in Separated Flow	101
6.4 Vaporization	105
6.4.1 Classes of Vaporization	105
6.4.2 Homogeneous Vaporization	105
6.4.3 Effect of Interfacial Roughness	108
6.5 Heterogeneous Vaporization	108
6.5.1 Pool Boiling	108
6.5.2 Pool Boiling on a Horizontal Surface	109

6.5.3	Nucleate Boiling	111
6.5.4	Pool Boiling Crisis	113
6.5.5	Film Boiling	115
6.5.6	Boiling on Vertical Surfaces	116
6.6	Multiphase Flow Instabilities	118
6.6.1	Introduction	118
6.6.2	Concentration Wave Oscillations	119
6.6.3	Ledinegg Instability	119
6.6.4	Chugging and Condensation Oscillations	120
6.7	Nuclear Reactor Context	124
7	Reactor Multiphase Flows and Accidents	127
7.1	Multiphase Flows in Nuclear Reactors	127
7.1.1	Multiphase Flow in Normal Operation	127
7.1.2	Void Fraction Effect on Reactivity	128
7.1.3	Multiphase Flow during Overheating	128
7.2	Multiphase Flows in Nuclear Accidents	130
7.3	Safety Concerns	130
7.4	Safety Systems	131
7.4.1	PWR Safety Systems	132
7.4.2	BWR Safety Systems	133
7.5	Major Accidents	134
7.5.1	Three Mile Island	134
7.5.2	Chernobyl	137
7.5.3	Fukushima	140
7.5.4	Other Accidents	141
7.6	Hypothetical Accident Analyses	142
7.6.1	Hypothetical Accident Analyses for LWRs	142
7.6.2	Loss-of-Coolant Accident: LWRs	143
7.6.3	Loss-of-Coolant Accident: LMFBRs	145
7.6.4	Vapor Explosions	146
7.6.5	Fuel–Coolant Interaction	147
7.7	Hypothetical Accident Analyses for FBRs	147
7.7.1	Hypothetical Core Disassembly Accident	148
	<i>Index</i>	151