

Fundamentals of Nuclear Reactor Physics

E. E. Lewis

*Professor of Mechanical Engineering
McCormick School of Engineering and Applied Science
Northwestern University*



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Academic Press is an imprint of Elsevier



Contents

Preface	xiii
1 Nuclear Reactions	1
1.1 Introduction	1
1.2 Nuclear Reaction Fundamentals	2
Reaction Equations	3
Notation	5
Energetics	5
1.3 The Curve of Binding Energy	7
1.4 Fusion Reactions	8
1.5 Fission Reactions	9
Energy Release and Dissipation	10
Neutron Multiplication	12
Fission Products	13
1.6 Fissile and Fertile Materials	16
1.7 Radioactive Decay	18
Saturation Activity	20
Decay Chains	21
2 Neutron Interactions	29
2.1 Introduction	29
2.2 Neutron Cross Sections	29
Microscopic and Macroscopic Cross Sections	30
Uncollided Flux	32
Nuclide Densities	33
Enriched Uranium	35
Cross Section Calculation Example	36
Reaction Types	36
2.3 Neutron Energy Range	38
2.4 Cross Section Energy Dependence	40
Compound Nucleus Formation	41
Resonance Cross Sections	42
Threshold Cross Sections	46
Fissionable Materials	47

2.5	Neutron Scattering	48
	Elastic Scattering	49
	Slowing Down Decrement	50
	Inelastic Scattering	52
3	Neutron Distributions in Energy	57
3.1	Introduction	57
3.2	Nuclear Fuel Properties	58
3.3	Neutron Moderators	61
3.4	Neutron Energy Spectra	63
	Fast Neutrons	65
	Neutron Slowing Down	66
	Thermal Neutrons	70
	Fast and Thermal Reactor Spectra	72
3.5	Energy-Averaged Reaction Rates	73
	Fast Cross Section Averages	75
	Resonance Cross Section Averages	78
	Thermal Cross Section Averages	79
3.6	Infinite Medium Multiplication	81
4	The Power Reactor Core	85
4.1	Introduction	85
4.2	Core Composition	85
	Light Water Reactors	88
	Heavy Water Reactors	91
	Graphite-Moderated Reactors	92
	RBMK Reactors	93
	Fast Reactors	94
4.3	Fast Reactor Lattices	94
4.4	Thermal Reactor Lattices	98
	The Four Factor Formula	99
	Pressurized Water Reactor Example	108
5	Reactor Kinetics	115
5.1	Introduction	115
5.2	Neutron Balance Equations	116
	Infinite Medium Nonmultiplying Systems	116
	Infinite Medium Multiplying Systems	117
	Finite Multiplying Systems	119
5.3	Multiplying Systems Behavior	120
5.4	Delayed Neutron Kinetics	123
	Kinetics Equations	124
	Reactivity Formulation	126

5.5	Step Reactivity Changes	126
	Reactor Period	127
	Prompt Jump Approximation	131
5.6	Prologue to Reactor Dynamics	133
6	Spatial Diffusion of Neutrons	139
6.1	Introduction	139
6.2	The Neutron Diffusion Equation	140
	Spatial Neutron Balance	140
	Diffusion Approximation	142
6.3	Nonmultiplying Systems—Plane Geometry	143
	Source Free Example	143
	Uniform Source Example	144
6.4	Boundary Conditions	145
	Vacuum Boundaries	146
	Reflected Boundaries	147
	Surface Sources and Albedos	147
	Interface Conditions	148
	Boundary Conditions in Other Geometries	149
6.5	Nonmultiplying Systems—Spherical Geometry	149
	Point Source Example	150
	Two Region Example	151
6.6	Diffusion Approximation Validity	153
	Diffusion Length	154
	Uncollided Flux Revisited	155
6.7	Multiplying Systems	157
	Subcritical Assemblies	157
	The Critical Reactor	160
7	Neutron Distributions in Reactors	167
7.1	Introduction	167
7.2	The Time-Independent Diffusion Equation	167
7.3	Uniform Reactors	169
	Finite Cylindrical Core	170
	Reactor Power	172
7.4	Neutron Leakage	174
	Two Group Approximation	174
	Migration Length	178
	Leakage and Design	179
7.5	Reflected Reactors	180
	Axial Reflector Example	181
	Reflector Savings and Flux Flattening	184

7.6	Control Poisons	186
	Reactivity Worth	186
	Partially Inserted Control Rod	188
	Control Rod Bank Insertion	190
8	Energy Transport	199
8.1	Introduction	199
8.2	Core Power Distribution	199
	Finite Cylindrical Core	200
	Uniform Cylindrical Core Example	203
8.3	Heat Transport	204
	Heat Source Characterization	204
	Steady State Temperatures	205
	Pressurized Water Reactor Example	209
8.4	Thermal Transients	211
	Fuel Temperature Transient Examples	212
	Coolant Temperature Transients	213
9	Reactivity Feedback	221
9.1	Introduction	221
9.2	Reactivity Coefficients	221
	Fuel Temperature Coefficient	223
	Moderator Temperature Coefficient	225
	Fast Reactor Temperature Coefficients	227
9.3	Composite Coefficients	227
	Prompt Coefficient	228
	Isothermal Temperature Coefficient	228
	Power Coefficient	229
	Temperature and Power Defects	230
9.4	Excess Reactivity and Shutdown Margin	230
9.5	Reactor Transients	232
	Reactor Dynamics Model	233
	Transient Analysis	234
10	Long-Term Core Behavior	243
10.1	Introduction	243
10.2	Reactivity Control	243
10.3	Fission Product Buildup and Decay	245
	Xenon Poisoning	247
	Samarium Poisoning	250
10.4	Fuel Depletion	252
	Fissionable Nuclide Concentrations	252
	Burnable Poisons	255
10.5	Fission Product and Actinide Inventories	257

Appendices	263
A Useful Mathematical Relationships	265
Derivatives and Integrals	265
Definite Integrals	265
Hyperbolic Functions	266
Expansions	266
Integration by Parts	266
Derivative of an Integral	267
First-Order Differential Equations	267
Second-Order Differential Equations	268
∇^2 and dV in Various Coordinate Systems	268
B Bessel's Equation and Functions	269
C Derivation of Neutron Diffusion Properties	273
D Fuel Element Heat Transfer	279
E Nuclear Data	283
 Index	 287