

Contents

Part I Neutronics

1 Fundamentals of Nuclear Physics	3
1.1 Chemical Elements	3
1.2 Molecules	7
1.3 Isotopes	9
1.4 Atoms	12
1.5 Avogadro's Number	14
1.6 Mass-Energy Equivalence	19
1.7 Neutrons	22
1.8 Electrons	25
1.9 Protons	28
1.10 The Electron Cloud	28
1.11 The Atomic Nucleus	40
1.12 Nuclear Spin	50
1.13 Radioactivity	51
1.13.1 Alpha Decay	61
1.13.2 β^- Decay	68
1.13.3 β^+ Radioactivity	71
1.13.4 Electron Capture	72
1.13.5 γ Radioactivity	73
1.13.6 Internal Conversion	74
1.13.7 (β^-, n) Decay or Neutron Decay	75
1.13.8 Spontaneous Fission	76
1.14 Radioactive Decay Branches	76
1.15 Heavy Nucleus Chains	82
2 Interaction Between Neutrons and Matter	89
2.1 Neutron Scattering	89
2.1.1 Elastic Scattering on a Fixed Target	90
2.1.2 Elastic Scattering on a Moving Target	97

	2.1.3 Moderator	99
	2.1.4 Inelastic Scattering	100
2.2	Transmutations	103
	2.2.1 Absorption	104
	2.2.2 (n,γ) Neutron Capture or Radiative Capture	105
	2.2.3 (n,α) Capture	106
	2.2.4 Other Forms of Capture	106
	2.2.5 High-Energy Reactions	107
	2.2.6 Energy Balance	107
2.3	Fission	110
2.4	Fusion	110
2.5	Cross Sections	111
	2.5.1 Basic Definitions	111
	2.5.2 Measurement of Cross Sections	113
	2.5.3 Notion of Flux and Reaction Rate	114
	2.5.4 Resonance	116
2.6	Nuclear Fission	128
	2.6.1 Fission Energy	131
	2.6.2 Spontaneous Fission	133
	2.6.3 Neutrons Produced by Fission	134
	2.6.4 Prompt Fission Photons	142
	2.6.5 Delayed Fission Neutrons	143
2.7	Fission Products Resulting from Fission	147
	2.7.1 Direct Yield of an Isotope	149
	2.7.2 Total Chain Yield	150
	2.7.3 Cumulative Yield of an Isotope	151
	2.7.4 Slowing Down of Fission Products in Matter	151
3	Interaction of Electromagnetic Radiation and Charged Particles with Matter	153
3.1	Electromagnetic Radiation	153
3.2	X-radiation	154
3.3	Interaction of Photons with Matter	157
	3.3.1 Attenuation of a Photon Beam	158
	3.3.2 Photon Transport	160
	3.3.3 Rayleigh-Thomson Scattering	161
	3.3.4 Photoelectric Effect	161
	3.3.5 Compton Effect	166
	3.3.6 Pair Production	171
	3.3.7 Cumulative Effects	174
	3.3.8 Scattered Radiation and Build-Up Factors	174
	3.3.9 Application of Photon Attenuation in Matter	177
	3.3.10 Photoneutrons	181
	3.3.11 Photofission	182
3.4	Measuring Radiation	182

	3.5 Interaction of Electrons with Matter	184
	3.5.1 Ionization	186
	3.5.2 Wilson Chamber	187
	3.5.3 Excitation	189
	3.5.4 Braking Radiation or Bremsstrahlung	189
	3.5.5 Annihilation	190
	3.6 Cherenkov-Mallet Effect	190
	3.7 Charged Particles: Rutherford Diffusion	193
	3.8 Transfer of Energy to Matter	198
	3.9 Ion-Electron Pair Production by Ionization	204
	3.10 Variation in Charge	205
	3.11 Fission Products	205
	3.12 Path Length in Matter	206
	3.13 Biological Effects of Radiation	207
4	Neutron Slowing-Down	211
4.1	Historical Background	211
4.2	Continuous-Energy Slowing-Down Theory	214
	4.2.1 Elastic Collision with a Stationary Target	215
	4.2.2 Collision Statistics	223
	4.2.3 Effect of the Motion of the Target Nucleus	226
	4.2.4 Transfer Probability as a Function of Angle	227
	4.2.5 Isotropic Collision	230
4.3	Continuous Slowing-Down Theory	231
	4.3.1 Slowing Down by Non-Absorbing Hydrogen	237
	4.3.2 Taking into Account Absorption by Hydrogen	246
	4.3.3 Taking Account of a Spectral Source	247
	4.3.4 Slowing Down by Targets Heavier Than Hydrogen	248
	4.3.5 Influence of the Fast Fission Spectrum	256
	4.3.6 Mixture of Moderators	259
4.4	Slowing Down in an Absorbing Medium	260
	4.4.1 Slowly Varying Absorption: The Greuling-Goertzel Model	265
	4.4.2 Slowing Down in a Medium with a Resonant Cross Section	268
	4.4.3 Inelastic Slowing-Down	271
	4.4.4 The Q_n Slowing-Down Approximation	275
5	Resonant Absorption	281
5.1	Cross Section Model	281
	5.1.1 Historical Background	281
	5.1.2 Intermediate Nucleus Theory	282
	5.1.3 Principle of Reciprocity	285

5.2	Single-Level Breit-Wigner Formalism	286
5.2.1	Total Cross Section	287
5.2.2	Scattering Cross Section	288
5.2.3	Radiative Capture Cross Section	288
5.2.4	Fission Cross Section	290
5.2.5	Absorption Cross Section	290
5.2.6	Negative Resonances	291
5.2.7	Distribution of Resonances	291
5.2.8	Resonant Absorption	294
5.3	Self-Shielding	295
5.4	Slowing-Down Through Resonances	298
5.5	The Livolant-Jeanpierre Formalism	301
5.5.1	Homogeneous Medium	301
5.5.2	Fine Structure Equation	304
5.5.3	Tabulating Effective Cross Sections	306
5.6	Modeling the Slowing-Down Operator Using the Resonant Isotope	308
5.6.1	Narrow Resonance Approximation	308
5.6.2	Wide Resonance Approximation	309
5.6.3	Statistical Approach	310
5.6.4	All Resonance Model (TR)	311
5.7	Heterogeneous Medium	313
5.7.1	Two-Media Problem	313
5.7.2	Accounting for Spatial Interaction	317
5.7.3	Generalization to Several Self-Shielding Regions	320
5.8	Accounting for Energy Interactions: Self-Shielding of Mixtures	322
5.9	Intermediate Resonance Model in Flux Calculations	323
5.10	The Probability Table Method	326
6	Doppler Effect	333
6.1	An Intuitive Analysis of the Doppler Effect	333
6.2	Effective Interaction Cross Section with “Hot” Matter	334
6.2.1	Distribution of the Target Nuclei Velocities in Matter: The Free Gas Model	335
6.2.2	Definition of the Effective Cross Section	336
6.2.3	Cross Section Inversely Proportional to Velocity	337
6.2.4	Constant Cross Section	337
6.3	Generalized Doppler Broadening: Bethe-Placzek Formula	341
6.4	Doppler Broadening of a Breit-Wigner Cross Section	345
6.4.1	Overview of the Breit-Wigner Formalism	345
6.4.2	Voigt’s Formula	347
6.4.3	Interference Function	353
6.5	Application to the Large Resonance of Uranium 238	354

6.6	Temperature Effect on Cross Sections	356
6.6.1	First Voigt Function ψ	357
6.6.2	Interference Function	358
6.6.3	Asymptotic Numeric Evaluation	359
6.6.4	Derivatives of the Voigt Functions with Respect to Energy	362
6.6.5	Some Mathematical Properties of Voigt Profiles	363
6.7	Effective Resonance Integral	364
6.7.1	Homogeneous Medium	364
6.7.2	Heterogeneous Medium	367
6.7.3	Analytical Calculation of a Broadened Resonance: The Campos-Martinez Model	374
6.8	Effective Doppler Temperature	378
6.8.1	Lattice Bonding Effects	378
6.8.2	Heterogeneity Effects of the Temperature Field	380
7	Thermalization of Neutrons	387
7.1	Historical Background	387
7.2	Boltzmann Theory of Gases	388
7.3	Application to Neutrons	392
7.4	Neutron Flux Spectrum	395
7.5	Neutron Thermalization Equation	397
7.6	Wigner-Wilkins Model: Free Proton Gas	401
7.7	Asymptotic Spectrum	404
7.8	Simplified Solution to Thermalization with Absorption	408
7.9	Horowitz-Tretiakoff Model	412
7.9.1	Principle	412
7.9.2	Case of Absorption Inversely Proportional to Speed	419
7.9.3	Case of a Finite Reactor (with Leakage)	419
7.9.4	Thermalization Equation for a Homogeneous Medium	420
7.10	Heavy Gas Model	421
7.11	Cadilhac, Horowitz and Soulé Differential Model	422
7.12	Application of the Cadilhac Model to Heterogeneous Media	426
7.13	Graphical Representation of Flux over the Energy Spectrum	431
7.14	True Moderators	432
7.15	Heating and Cooling by Scattering	434
7.16	Thermalized Absorption	437
7.16.1	Calculation of Reaction Rate in a Pure Thermal Spectrum	440
7.16.2	Definition of the Westcott Coefficient $g_{(T)}$	441
7.17	Calculation of the Reaction Rate in a True Thermal Spectrum	446

7.17.1	Westcott Formalism: Introduction of the Coefficients r and s	449
7.17.2	Extension of the Model to Other Nuclides: The Linear Logarithmic Model	453
7.17.3	Progressive Junction at Epithermal Energy	456
7.17.4	Westcott Junction	457
7.17.5	Determination of Cut-Off Function	458
7.17.6	Limits of the Westcott Formalism	460
7.18	Application of the Westcott Formalism	461
8	The Boltzmann Equation	465
8.1	Setting Up the Boltzmann Equation	465
8.1.1	Concept of Flux	468
8.2	The Integro-Differential Transport Equation	474
8.2.1	The Integro-Differential Transport Equation in Kinetics	474
8.2.2	The Integro-Differential Equation in Steady-State	475
8.3	Integral Form of the Boltzmann Equation	507
8.3.1	Peierls Operator	507
8.3.2	The Volume Integral Form	510
8.3.3	The First Collision Probability	512
8.3.4	1D Geometry	522
8.3.5	Escape Probabilities	524
8.3.6	The Integral Equation in 2D	538
8.3.7	Application to an Infinite Medium with a Fission Source	539
8.3.8	Graphical Solution to the Dispersion Equation	540
8.4	Third Form of the Transport Equation: the Surface-Integral Form	543
8.4.1	Placzek's Lemma	544
8.4.2	Flux Equation at the Interface	546
8.4.3	Application to the Milne Problem	547
8.4.4	Second Complementarity Theorem	548
8.5	Concept of Characteristic Function	549
8.6	Fourier Transform of the Boltzmann Equation	553
8.6.1	Formalism	553
8.6.2	Resolution Using Green's Function	555
8.7	The 1D Transport Equation	559
8.7.1	General Points	559
8.7.2	Lafore and Millot Method, Case Method	562
8.7.3	Perovich Method	571
8.8	Asymptotic Solution for Diffusion	572
8.8.1	Exponential Relaxation of the Flux, Far from the Source	572

8.8.2	Finding the Dispersion Equation from the Asymptotic Flux	580
8.8.3	Critical Absorption Limiting the Asymptotic Solution	582
8.8.4	Definition of a Diffusion Coefficient from the Transport Equation	584
8.9	The 3D Transport Equations	589
9	Computational Neutron Transport Methods	593
9.1	Discrete Ordinates Method S_n	593
9.2	Exact S_n Method	601
9.3	Legendre Polynomial Method	604
9.3.1	Theory and Application to 1D Transport	604
9.3.2	Multi-group 1D Transport and Diffusion Equivalence	619
9.4	SP_n Method	623
9.5	Interfaces Between Different Media	628
9.6	Spherical Harmonics Method	630
9.6.1	Principle	630
9.6.2	P_1 Approximation	638
9.7	Milne Problem	640
9.8	DP_n Method	643
9.9	Semi-infinite Plane: Albedo Problem	646
9.9.1	Fundamentals of Discrete Eigenfunctions	646
9.9.2	Ganapol Method by Laplace Transform	652
9.10	B_n Method	657
9.11	T_n Method	667
9.12	F_n Method	670
9.13	C_n Method	670
9.14	The SK_n Method	675
9.15	Method of Characteristics (MOC)	677
9.15.1	Principle	677
9.15.2	Heterogeneous Geometries	679
9.15.3	Characteristic Direction Probabilities (CDP)	684
9.16	Even–Odd Formulation of the Transport Equation	686
9.16.1	Even–Odd Flux Equation	687
9.16.2	Variational Nodal Method of the Even–Odd Formulation	691
9.16.3	Ritz Method	694
9.17	Variational Method for Time-Dependent Problems	697
9.18	Gauss-Seidel Method for Sources in Time-Dependent Problems	699
9.19	Probabilistic Approach: The Monte Carlo Method	700
9.19.1	Fundamental Concepts of the Monte Carlo Method	700

9.19.2	Application to Neutron Transport: A Simple 2D Case	705
9.19.3	Statistical Error	713
9.19.4	Calculation of Physical Quantities	713
9.19.5	Generalization, Biasing	714
9.19.6	Resonance Escape Probability Factor Calculation	716
9.19.7	Midway Monte Carlo	719
9.19.8	Quasi-Deterministic Approximation of the Importance Function	723
9.19.9	Example of a Monte Carlo Calculation	726

Contents for Volume 2

Part II Reactor Physics

10	Diffusion Approximation in Neutron Physics	731
10.1	Fick's Law	731
10.1.1	Evaluation of the Neutron Diffusion Coefficient	731
10.1.2	Discussion of the Hypotheses	736
10.1.3	The Diffusion Equation in a Force Field	741
10.2	Boundary Conditions for a Medium Surrounded by a Vacuum in Diffusion Theory	743
10.2.1	P_1 Approximation	744
10.2.2	Rulko's Variational Approach	745
10.3	Boundary Conditions Between Any Two Media	749
10.3.1	Notion of a Reflector Albedo	750
10.4	Diffusion Equation in Energy	751
10.5	One-Group Diffusion Equation	753
10.6	"Thermal Diffusion"	755
10.6.1	"Thermal" Diffusion Equation	755
10.6.2	Interpretation of the Thermal Scattering Path	757
10.6.3	Deriving the Four-Factor Formula	759
10.7	Scattering of an Isotropic Source in a Non-Multiplying Medium	759
10.7.1	Point Source in an Infinite Scattering Medium	760
10.7.2	Anisotropic Point Source in Spherical Geometry	763
10.7.3	Infinite Thin Rod Source in an Infinite Scattering Medium	769
10.7.4	Infinite Plane Source in an Infinite Scattering Medium	771
10.7.5	Infinite Plane Source in an Infinite Scattering Slab	773
10.7.6	Uniform Source in an Infinite Scattering Slab	775
10.7.7	Semi-infinite Slab Source	776

10.7.8	Extension to the Infinite Homogeneous Medium	778
10.7.9	Expansion on the Eigenfunctions of the Laplacian Operator	779
10.7.10	Superposition of Flux Induced by Point Sources	780
10.7.11	Absorbing Slab in an Infinite Source Medium	782
10.7.12	Thin Absorbing Slabs, the Galanin Method	783
10.7.13	Flux Transient	784
10.8	Measurement of the Scattering Path of a Moderator by Attenuation	787
10.9	Pulsed Neutron Method	791
10.10	Diffusion in a Homogeneous Slab	797
10.11	Source Thermalization Transient in Diffusion Theory	802
10.11.1	Infinite Medium	802
10.11.2	Finite Medium	803
10.11.3	Expansion on Eigenfunctions	804
10.11.4	Case of a Pulsed Source	806
10.12	Polykinetic Diffusion	808
11	Nuclear Reactor Reactivity	815
11.1	Multiplication Factor of a Chain Reaction	815
11.1.1	Deterministic Approach to Chain Reactions	815
11.1.2	Stochastic Approach to Chain Reaction	816
11.2	"Four-factor" Formula	821
11.2.1	Detailed Analysis of the Four-factor Formula	822
11.2.2	Technological Moderation Ratio Effect on the Four-factor Formula	827
11.3	Allowing for Leakages in a Finite Reactor	828
11.4	Two-group Multiplication Factor	829
11.5	Multiplication Factor Through a Reaction Rate Balance	835
11.6	Reactivity Effects or Reactivity Difference	840
11.6.1	Comparison of the Effects on a UOX Fuel	841
11.6.2	Reactivity Effect of Isotopic Change	842
11.7	Calculation of Reactivity by Perturbation Theory Estimate	845
11.8	Evolution of the Reactivity Along the Cycle	847
12	Critical Homogeneous Reactor Theory	849
12.1	Introduction	849
12.2	The Notion of Geometrical and Material Buckling	854
12.3	Criticality Condition	855
12.4	Notion of Critical Size: The Rod Model	856
12.4.1	Analysis of Criticality	856
12.4.2	Invariant Imbedding	860
12.5	Fundamental Mode for a Reactor with Simple Geometry	864
12.5.1	Plane Slab	864
12.5.2	Parallelepiped	868
12.5.3	Infinite Cylinder	870

12.5.4	Finite Cylinder	873
12.5.5	Disc	875
12.5.6	Sphere	878
12.5.7	Hemisphere	881
12.5.8	Polygon	882
12.5.9	Accounting for Singularities in 2D	884
12.5.10	Anisotropic Point Source in a Multiplying Medium	892
12.5.11	Zero Flux Distance	893
12.5.12	Annular Reactor	895
12.6	Any Three-Dimensional Reactor	899
12.7	Fermi Age Theory	900
12.7.1	History	901
12.7.2	Overview of Slowing-Down	902
12.7.3	Application to Neutron Diffusion	904
12.7.4	Relation Between Fermi Age and Time	905
12.7.5	Link Between the Age Theory and Diffusion Theory	907
12.7.6	Two-Energy Group Equation in Fermi Age Theory	909
12.7.7	Age-Diffusion Theory	912
12.8	Multi-Group Diffusion	912
12.9	Reactor Kinetics in One-Group Diffusion Theory with Source	914
12.10	Source Calculation: Extension to Multi-Group Conditions	916
13	Neutron Reflectors	919
13.1	Some Mathematical Considerations on Reflectors	919
13.2	Reflectors in Diffusion Theory	922
13.2.1	Case of the Slab Reactor Surrounded by an Infinite Reflector	922
13.2.2	Reflected Homogeneous Slab Reactor	926
13.2.3	Case of an Infinite Cylindrical Reactor Surrounded by an Infinite Reflector	928
13.2.4	Case of an Infinite Cylindrical Reactor with a Finite Reflector	934
13.3	Definition of Reflector Albedo	939
13.3.1	Albedo Calculation for a Slab Reflector	941
13.3.2	Albedo Calculation of a Cylindrical Reflector	942
13.3.3	Albedo of a Spherical Reflector	942
13.3.4	Albedo Calculation for the Upper Reflector of a Cylindrical Reactor	943
13.3.5	Extrapolation and Null-flux Distances	944
13.3.6	Numerical Example	947
13.4	Reflector Theory with Two Energy Groups	947
13.4.1	Slab Reflector	948

13.4.2	Infinite Cylindrical Reactor with Reflector in Two Groups Without Up-Scattering	949
13.4.3	Flux Calculation in the Fuel	950
13.4.4	Flux in the Reflector	952
13.5	Slab Reactor with Finite Reflector and Without Up-Scattering	955
13.6	The Ackroyd "Magic Shell" Albedo Model	957
13.7	The Lefebvre-Lebigot Reflector Model	959
13.7.1	"Equivalent" Reflectors Theory	960
13.7.2	Calculation of Core Characteristics	965
13.7.3	Core/Reflector Operating Point	967
13.7.4	Effect of Thermal-Hydraulic Feedbacks	969
13.7.5	Calculation of Constants in the Mathematical Reflector	970
13.8	Albedo Matrix	971
13.9	Allowing for Up-Scattering	972
13.10	Diffusion/Transport Correspondence	977
13.11	Reuss-Nisan Model	978
13.12	Mondot Model	984
13.13	Generalized BETA Method	986
13.14	Absorption in the Reflector	987
13.15	Double-Differential Albedo	988
14	Heterogeneous Reactors	991
14.1	Why Is Heterogeneity Desirable?	991
14.2	Gurevich-Pomeranchuk Heterogeneous Resonant Absorption Theory	993
14.2.1	Theoretical Background	993
14.2.2	Effective Resonance Integral	998
14.3	Modeling the Pin Flux	999
14.3.1	First-Collision Probability	1000
14.3.2	The Amouyal-Benoist-Horowitz (<i>A-B-H</i>) Theory	1002
14.3.3	Multi-cell Approach in Two Dimensions	1014
14.3.4	Carlvik Rational Approximation	1032
14.3.5	Heterogeneity of the Isotopic Composition	1038
14.3.6	Shadowing Effect on the Resonance Integral	1038
14.3.7	Heterogeneous $P_{i,j}$ Calculations for Fast Reactors with Perturbation Methods	1042
14.4	Transport-Diffusion Equivalence	1045
14.4.1	Context	1045
14.4.2	Spatial Homogenization	1047
14.4.3	Multi-group Approach	1048
14.4.4	Kavenoky-Hébert SPH Equivalence	1049
14.4.5	Flux Reconstruction Between Different Operators	1051

14.4.6	Spatial Homogenization with Leakage	1062
14.4.7	Equivalence for Slab Reactors	1067
14.4.8	Equivalence by Conservation of Reaction Rates	1072
14.5	Homogenization Theory in Diffusion	1076
14.5.1	Flux-Volume Homogenization	1076
14.5.2	Homogenization of Heterogeneous Neutron Quantities	1077
14.5.3	Average Flux Homogenization at the Boundary, Selengut Normalization	1080
14.5.4	Pin Power Reconstruction	1082
14.5.5	Discontinuity Factors	1087
15	Fuel Cycle Physics	1091
15.1	Schematic Notation for Fuel Cycle Physics	1091
15.2	Disintegration	1092
15.3	Neutron-Induced Reactions	1092
15.4	The Bateman Equations	1092
15.4.1	Heavy Nuclides	1093
15.4.2	Fission Products	1095
15.4.3	Activation Products	1096
15.5	Vectorial Form of the Bateman Equation	1097
15.6	Calculation of Relevant Quantities for the Fuel Cycle	1097
15.6.1	Mass Balance	1097
15.6.2	Burn-up	1098
15.6.3	Activity	1104
15.6.4	Calculation of Decay Heat	1104
15.6.5	<i>Photon γ</i> and Neutron Dose Calculation	1115
15.7	Isotopic Depletion Calculation	1117
15.7.1	Chain-Decay Process: Recurrence Relations	1118
15.7.2	Case of Heavy Nuclides	1121
15.7.3	Case of Fission Products	1122
15.7.4	Reference Composition of Some PWR Fuel	1123
15.8	Decay Chain Reduction Principle	1124
15.8.1	Heavy Nuclide Chain for Reactivity Calculations of Reactors	1126
15.8.2	Decay Chain Reduction	1134
15.9	Activation: The Example of Control Rods	1137
15.10	Xenon Physics	1138
15.10.1	Production of Xenon	1138
15.10.2	Xenon Saturation	1140
15.10.3	Xenon Poisoning After Reactor Shutdown	1142
15.11	Samarium Physics	1144
15.12	Gadolinium Physics	1145
15.13	The Industrial Fuel Cycle in France	1146

16	Neutronic Feedback	1153
16.1	Effect of Fuel Temperature on the Multiplication Factor	1153
16.1.1	Fuel Doppler Effect	1153
16.1.2	Doppler Effect on Reactor Behavior	1156
16.2	Moderator Temperature Effect	1158
16.2.1	Definitions	1158
16.2.2	Leakage and Absorber Effects	1160
16.2.3	Pressure Effect	1162
16.2.4	Graphite Moderator	1163
16.2.5	Neutron Spectrum Shift	1164
16.2.6	Void Effect	1165
16.3	Boron Effect in Pressurized Water Reactors	1166
16.3.1	Differential Efficiency of Boron	1166
16.3.2	Boron Effect on the Moderator Differential Coefficient	1167
16.4	Power Coefficient	1168
16.5	Feedback Modeling	1168
16.5.1	A Simple Model: Power Feedback	1171
16.5.2	An Advanced Feedback Model: The Lefebvre-Seban Model	1172
16.6	Historical Isotopic Correction	1183
17	Reactor Kinetics	1187
17.1	Prompt Neutrons	1187
17.1.1	Evolution of a Hypothetical Prompt Neutron Reactor	1188
17.1.2	Flux Calculation: Point Reactor Hypothesis	1193
17.2	Delayed Neutrons	1195
17.2.1	Delayed Neutron Fraction	1199
17.3	Effect of Delayed Neutrons on Reactor Kinetics	1200
17.4	Neutron Kinetics Equation	1203
17.4.1	Precursor Concentration	1205
17.4.2	Point-Reactor Kinetics	1206
17.4.3	Mobile Fuel	1208
17.5	Nordheim Equation	1208
17.6	"Prompt Jump" Notion: Insertion of a Reactivity Step	1213
17.7	Age Theory in the Kinetics Equation for Thermal Neutrons	1215
17.8	Reduced Kinetics Equations	1218
17.9	Kinetics with an Imposed Neutron Source	1220
17.10	Delayed Neutron Spectrum	1221
17.11	First-Order Perturbations	1229
17.12	Numerical Reactimeter	1231
17.13	Practical Evaluation of Prompt Neutron Generation Time	1234
17.14	Main Causes of Reactivity Changes	1236
17.14.1	Increased Fissile Nuclei	1236

17	17.14.2 Increased Neutron Moderation	1237
17.14.3	Decreased Neutron Capture	1237
17.15	Reactivity Accident: Insertion of Very High Reactivity Value	1238
17.15.1	Analysis with One Group of Delayed Neutrons	1238
17.15.2	Analysis of the Case of $\rho \gg \beta$: The Reactivity Accident	1241
17.15.3	Insertion of Low Reactivity $0 \leq \rho \ll \beta$	1243
17.16	Anti-reactivity Insertion	1245
17.17	Overview of Cases	1246
17.18	Reactivity Step	1247
17.19	Dropped Control Rod, Insertion of a Large Amount of Anti-reactivity	1249
17.20	Reactivity Ramp	1250
17.21	Reactivity Transient	1254
17.22	Power Excursion	1254
17.22.1	The Nordheim-Fuchs Model	1255
17.22.2	The Chernick Model	1259
17.22.3	The Bethe-Tait Model	1262
17.23	Subcritical Approach: Reactor Start-Up	1266
17.24	Reactor Stability	1267
17.25	Space-Time Xenon Oscillations	1271
17.26	Mechanical Kinetic Effects	1276
17.27	Neutron Noise	1277
17.27.1	Noise Concept, Spectral Analysis	1278
17.27.2	Neutron Correlations	1280
17.27.3	The Feynman- α Method	1287
17.27.4	Delayed-Neutron Effect	1295
17.27.5	Application to Measurement of Void Fraction Instabilities	1296
17.27.6	Application to Detection of Vibrations	1298
18	Computation Methods in Diffusion Theory	1301
18.1	Calculation Meshes	1301
18.2	Multi-group Diffusion Equations	1304
18.2.1	General Case	1304
18.2.2	"1.5"-group Diffusion	1305
18.2.3	Adjoint Diffusion	1305
18.2.4	Taking into Account the Neutron Over-Production Cross Sections	1307
18.3	The Power Iteration Method	1308
18.3.1	General Considerations	1308
18.3.2	Matrix Representation	1310
18.3.3	Chebyshev Acceleration	1312
18.4	Finite Difference Method	1315

18.4.1	Formalism	1315
18.4.2	Boundary Conditions	1320
18.4.3	Matrix Form	1321
18.5	Nodal Methods	1322
18.5.1	Nodal Method of Order 4	1324
18.5.2	Quadratic Approximation of Transverse Leakage . . .	1332
18.5.3	AFEN Method	1335
18.6	Finite Element Method	1336
18.7	Variational Methods	1340
18.7.1	Principle	1340
18.7.2	Accounting for Boundary Conditions	1342
18.8	Calculation of Control Rods	1343
18.8.1	Physical Effect of Rods	1344
18.8.2	Rod Worth: Perturbation Analysis	1345
18.8.3	Measuring Rod Efficiency in PWR	1348
18.8.4	Calculation of Rod Efficiency	1349
18.8.5	Analytical Decomposition of the Rodded Domain . .	1353
18.9	Instrumentation Considerations	1357
18.9.1	Modeling with Trace Quantities	1357
18.9.2	Modeling of the EPR Instrumentation: The <i>KTM</i> Model	1357
Conclusion	1367
Annex: Reactor Physics and Neutronic Codes at <i>Electricité de France</i>	1369
Bibliography	1403
Index	1431