

Contents

PREFACE	iii
CONTRIBUTORS	vi
1 HISTORICAL BACKGROUND	1
2 SOURCES OF RADIATION	11
2.1 Gamma-Ray and Neutron Sources	12
2.1.1 Gamma-Ray Sources	12
2.1.2 Neutron Sources	17
2.2 Basic Mathematical and Physical Concepts	19
2.2.1 Differential Distributions	19
2.2.2 Average and Most-Probable Values	24
2.2.3 Solid Angle	24
2.2.4 Measures of Radiation Intensity	26
2.3 Spatial and Directional Characteristics	39
2.3.1 Spatial Distributions	39
2.3.2 Directional Distributions	42
2.4 Energy Distributions	48
2.4.1 Energy Distributions of Gamma-Ray Sources	49
2.4.2 Neutron Spectra from Fission	54
2.4.3 Effect of Medium on Spectra	57
References	59
Exercises	60
3 INTERACTIONS OF RADIATION WITH MATTER	63
3.1 Cross Sections	63
3.1.1 Microscopic Cross Section	64
3.1.2 Macroscopic Cross Section	65
3.1.3 Radiation Reaction Rates	66
3.2 Radiation Interactions	67
3.2.1 Photon Interactions	68
3.2.2 Neutron Reactions	83
3.3 Responses to Radiation	94
3.3.1 Absorbed Dose	95
3.3.2 First-Collision Dose and Kerma	99
3.3.3 Exposure	103
3.3.4 RBE Dose; Dose Equivalent	105

3.3.5	Maximum Absorbed Dose; Maximum Dose Equivalent	108
3.3.6	Multicollision Dose	112
References	. . . . .	113
Exercises	. . . . .	114
4	RADIATION TRANSPORT	119
4.1	Fundamental Considerations	120
4.2	The Boltzmann Transport Equation	123
4.3	Spherical Harmonics Method	129
4.4	Discrete-Ordinates S_n Method	132
4.4.1	Transport Equation and Phase-Space Geometry	134
4.4.2	Derivation of Finite-Difference Equation	136
4.4.3	Numerical Solution of the Discrete-Ordinates Equation	144
4.4.4	Advantages and Disadvantages	148
4.5	Moments Method	149
4.6	Application of Diffusion Theory	160
4.7	Invariant Imbedding Method	163
4.8	Kernel Technique	168
4.8.1	Gamma-Ray Calculations	169
4.8.2	Neutron Techniques	178
4.9	Combination Removal–Diffusion Methods	188
4.9.1	The Spinney Method	190
4.9.2	Variations of the Spinney Method	192
4.9.3	Differences in Current Methods	199
References	. . . . .	201
Exercises	. . . . .	204
5	MONTE CARLO METHODS FOR RADIATION TRANSPORT	207
5.1	Sampling from Probability Distribution Functions	209
5.2	The Evaluation of Integrals	216
5.3	Source Parameters	218
5.3.1	Selection from an Energy Distribution	218
5.3.2	Selection of Spatial Point of the Source Particle	219
5.3.3	Selection of Initial Direction of Source Particle	221
5.3.4	Source-Biasing Parameters	223
5.4	Path Length	225
5.5	Collision Parameters	234
5.6	Particle Parameters After Collision	236
5.6.1	Neutron Elastic Scattering	236
5.6.2	Neutron Inelastic Scattering	238
5.6.3	Compton Scattering	240
5.6.4	Particle Absorptions	240
5.6.5	Calculation of Emergent-Direction Cosines	241
5.7	Particle Scoring	242
5.8	Statistical Variance	247
5.9	Demonstration Monte Carlo Program	251
5.10	Programming Suggestions	254

References	257
Exercises	258
6 SHIELD ATTENUATION CALCULATIONS	261
6.1 Analysis of the Source	261
6.2 Direct Solutions	263
6.3 Application of Parametric Data	264
6.3.1 Moments-Method Differential Energy Spectra	265
6.3.2 Monte Carlo	270
6.3.3 Measured Data	274
6.3.4 Fitted-Parameter Data	277
6.4 Simplified Solutions	283
6.4.1 Applications of Gamma-Ray Buildup Factors	284
6.4.2 Applications of Neutron-Removal-Theory Kernels	286
6.4.3 Other Point-Kernel Applications	288
6.4.4 Methods for Estimating Low-Energy Neutron-Flux Density	298
6.5 Application of Kernel Technique to Calculations of Secondary Gamma-Ray Dose	301
6.5.1 Calculation for Slab Shield	304
6.5.2 Calculation for Semi-Infinite Shield	308
References	310
Exercises	311
7 ALBEDOS, DUCTS, AND VOIDS	313
7.1 Introduction to Albedos	313
7.2 Definitions	315
7.2.1 Differential-Dose Albedos	316
7.2.2 Total-Dose Albedos	317
7.2.3 Other Albedos	318
7.3 Neutron Albedos	318
7.3.1 Fast-Neutron Albedos	319
7.3.2 Intermediate-Neutron Albedos	331
7.3.3 Thermal-Neutron Albedos	332
7.4 Gamma-Ray Albedos	341
7.5 Secondary-Gamma-Ray Albedos	350
7.6 Applications of Albedos	355
7.7 Ducts	356
7.8 Line-of-Sight Component	357
7.8.1 Rectangular Ducts	360
7.8.2 Rectangular Slots	363
7.8.3 Cylindrical Ducts	365
7.8.4 Cylindrical Annulus	366
7.9 Wall-Penetration Component	367
7.9.1 Application to Cylindrical Ducts	370
7.9.2 Application to Partially Penetrating Cylindrical Ducts	372
7.9.3 Comparison with Experiment	374
7.10 Wall-Scattered Component	375
7.10.1 Analog Monte Carlo Calculations	376

7.10.2	Albedo Methods	380
7.10.3	Additional Experimental Investigations	398
7.11	Voids	404
7.11.1	Single Voids	404
7.11.2	Small Random Voids	412
References	. . . . .	414
8	SHIELD HEATING, AIR TRANSPORT, SHIELD MATERIALS, AND SHIELD OPTIMIZATION	419
8.1	Shield Heating	419
8.1.1	Gamma-Ray Heating	420
8.1.2	Neutron Heating	426
8.1.3	Charged-Particle Heating	429
8.2	Air Transport	430
8.2.1	Infinite Air Medium	432
8.2.2	Air-Over-Ground Calculations	437
8.2.3	Air–Ground Interface Effects	439
8.3	Shield Materials	443
8.3.1	Considerations in Materials Selection	445
8.3.2	Shield Materials for Stationary Reactor Systems	447
8.3.3	Shield Materials for Mobile Reactor Systems	450
8.3.4	Comparison of Attenuation Properties	456
8.4	Shield Optimization	462
References	. . . . .	465
9	EXPERIMENTAL SHIELDING	471
9.1	Detectors for Shielding Experiments	472
9.1.1	Active Neutron Detectors	472
9.1.2	Passive Neutron Detectors	474
9.1.3	Active Gamma-Ray Detectors	475
9.1.4	Passive Gamma-Ray Detectors	476
9.1.5	Interpretations of Detector Output	476
9.2	Shield-Material Measurements	477
9.2.1	Reactors	477
9.2.2	Accelerators	493
9.2.3	Fixed Sources	503
9.3	Phenomenological Measurements	507
9.3.1	Air-Transport and Air–Ground Interface Experiments	507
9.3.2	Duct Penetration	514
References	. . . . .	516
10	SHIELD DESIGN	519
10.1	Iterations in the Shield Design	520
10.1.1	Preliminary Conceptual Design	521
10.1.2	Detailed Conceptual Design	522
10.1.3	Final Engineering Design	524
10.2	Fast Breeder: Enrico Fermi	527
10.2.1	The Reactor Plant	528
10.2.2	Shield Design Criteria	532

10.2.3	Reactor-Shield Systems	534
10.2.4	Shield Costs	548
10.2.5	Calculational Techniques	548
10.2.6	Comparison of Measurements and Calculations	553
10.3	Fast Breeder: Dounreay Fast Reactor	559
10.3.1	Calculational Model for Bulk Shield	562
10.3.2	Measurements	563
10.3.3	Effect of Streaming	565
10.4	Heavy Water, Natural Uranium: Ägesta	566
10.4.1	Description of Reactor and Shield	566
10.4.2	Calculational Model	567
10.4.3	Measurements	570
10.5	Boiling Water: Pathfinder	574
10.5.1	Calculations	578
10.5.2	Survey Measurements	579
10.6	Ship Propulsion: N.S. <i>Savannah</i>	579
10.6.1	Description of Ship, Reactor, and Main Shielding	580
10.6.2	Shielding for Refueling and Control-Rod Maintenance	581
10.6.3	Shield Design Criteria	583
10.6.4	Lead-Polyethylene Shield Construction	585
10.6.5	Attenuation Calculations	587
10.6.6	Measurements	591
10.6.7	Comparison of Measurements and Calculations	592
10.7	Space Power: SNAP-10A Flight Test	595
10.7.1	Shield Analysis	595
10.7.2	Flight-Test Results	598
	References	602
Appendix A:	GAMMA RAYS FROM INELASTIC NEUTRON SCATTERING AND FISSION	605
Appendix B:	NEUTRON FLUENCE-TO-KERMA CONVERSION FACTORS FOR STANDARD-MAN MODEL	611
Appendix C:	CYLINDRICAL TISSUE PHANTOM	616
Appendix D:	COORDINATE SYSTEMS, VECTOR OPERATIONS, AND LEGENDRE POLYNOMIALS	617
	D.1 Coordinate Systems	617
	D.2 Coordinate-System Transformation	617
	D.3 Vector Operators and Functions	619
	D.4 Dirac Delta Function	621
	D.5 Legendre Polynomials	622
	D.6 Associated Legendre Polynomials	623
	D.7 Associated Spherical-Harmonic Functions	625
Appendix E:	EXPOSURE BUILDUP FACTORS	626
Appendix F:	COEFFICIENTS FOR GAMMA-RAY BUILDUP FACTORS	628
Appendix G:	GRAPHS AND FORMULAS OF EXPONENTIAL INTEGRAL FUNCTIONS	642

Appendix H: TABLES OF ATTENUATION FUNCTIONS FOR FINITE SLAB GEOMETRY	653
Appendix I: RANDOM-NUMBER GENERATORS	663
I.1 Properties of Random-Number Generators (RNG's)	664
I.2 Recursion Equations for RNG's	665
I.3 Testing RNG's	668
I.3.1 Global Tests	669
I.3.2 Equidistribution	669
I.3.3 Independence	670
I.4 Pathological Numbers	671
I.5 Useful RNG's	672
Appendix J: DEMONSTRATION MONTE CARLO PROGRAM	674
Appendix K: MOMENTS-METHOD RESULTS FOR FISSION-NEUTRON PENETRATION IN Be, C, CH, CH₂, H, AND H₂O	687
Appendix L: GAMMA-RAY DIFFERENTIAL ENERGY SPECTRA FOR WATER AND LEAD	692
Appendix M: GRAPHS FOR NEUTRON ATTENUATION CALCULATIONS	700
Appendix N: GRAPHS OF THE ψ FUNCTION	717
Appendix O: CONSTANTS FOR EMPIRICAL EXPRESSIONS OF ALBEDO DATA	726
Appendix P: RADIATION PENETRATION OF CYLINDRICAL DUCTS	734
SOLUTIONS TO EXERCISES	737
AUTHOR INDEX	771
SUBJECT INDEX	775

