

Contents

Preface.....	xi
Acknowledgments.....	xiii
Authors.....	xv
1. Basic Radiation Physics Concepts and Units of Measurement.....	1
1.1 Introduction.....	1
1.2 Units of Measure and Physical Quantities.....	1
1.3 Radiological Standards.....	3
1.4 Units of Measure for Radiological Quantities.....	3
1.4.1 Synopsis of the 1973 Radiation Protection System.....	4
1.4.2 Synopsis of the 1990 Radiation Protection System.....	5
1.4.3 Values of Radiation Protection Quantities.....	6
1.5 Physical Constants and Atomic and Nuclear Properties.....	10
1.6 Summary of Relativistic Relationships.....	11
1.7 Energy Loss by Ionization.....	14
1.8 Multiple Coulomb Scattering.....	21
Problems.....	23
2. General Considerations for Accelerator Radiation Fields.....	25
2.1 Introduction.....	25
2.2 Primary Radiation Fields at Accelerators: General Considerations.....	25
2.3 Theory of Radiation Transport.....	27
2.3.1 General Considerations of Radiation Transport.....	27
2.3.2 The Boltzmann Equation.....	29
2.4 The Monte Carlo Method.....	30
2.4.1 General Principles of the Monte Carlo Technique.....	30
2.4.2 Monte Carlo Example: A Sinusoidal Angular Distribution of Beam Particles.....	32
2.5 Review of Magnetic Deflection and Focusing of Charged Particles.....	34
2.5.1 Magnetic Deflection of Charged Particles.....	34
2.5.2 Magnetic Focusing of Charged Particles.....	36
Problems.....	42
3. Prompt Radiation Fields due to Electrons.....	43
3.1 Introduction.....	43
3.2 Unshielded Radiation Produced by Electron Beams.....	43
3.2.1 Dose Rate in a Direct Beam of Electrons.....	43
3.2.2 Bremsstrahlung.....	44
3.2.3 Neutrons.....	49
3.2.3.1 Giant Photonuclear Resonance Neutrons.....	49
3.2.3.2 Quasi-Deuteron Neutrons.....	51
3.2.3.3 High-Energy Particles.....	52
3.2.3.4 Production of Thermal Neutrons.....	52
3.2.4 Muons.....	52

3.2.5	Summary of Unshielded Radiation Produced by Electron Beams	54
3.3	Electromagnetic Cascade: Introduction.....	54
3.4	Electromagnetic Cascade Process.....	57
3.4.1	Longitudinal Shower Development.....	58
3.4.2	Lateral Shower Development.....	61
3.5	Shielding of Hadrons Produced by Electromagnetic Cascade.....	62
3.5.1	Neutrons.....	62
3.5.2	High-Energy Particles	64
3.6	Synchrotron Radiation	64
3.6.1	General Discussion of the Phenomenon	65
3.6.2	Insertion Devices	68
3.6.3	Radiation Protection Issues Specific to Synchrotron Radiation Facilities.....	71
3.6.3.1	Operating Modes.....	71
3.6.3.2	Gas Bremsstrahlung: Straight Ahead.....	73
3.6.3.3	Gas Bremsstrahlung: Secondary Photons	74
3.6.3.4	Gas Bremsstrahlung: Neutron Production Rates	76
3.6.3.5	Importance of Ray Tracing.....	77
	Problems.....	79
4.	Prompt Radiation Fields due to Protons and Ions.....	81
4.1	Introduction	81
4.2	Radiation Production by Proton Beams	81
4.2.1	The Direct Beam: Radiation Hazards and Nuclear Interactions	81
4.2.2	Neutrons and Other Hadrons at High Energies	82
4.2.2.1	$E_0 < 10$ MeV	82
4.2.2.2	$10 < E_0 < 200$ MeV	83
4.2.2.3	200 MeV $< E_0 < 1.0$ GeV: "Intermediate" Energy	83
4.2.2.4	$E_0 > 1.0$ GeV: "High"-Energy Region	85
4.2.3	Sullivan's Formula	86
4.2.4	Muons	88
4.3	Primary Radiation Fields at Ion Accelerators	90
4.3.1	Light Ions (Ion Mass Number $A < 5$).....	90
4.3.2	Heavy Ions (Ions with $A > 4$).....	92
4.4	Hadron (Neutron) Shielding for Low-Energy Incident Protons ($E_0 < 15$ MeV).....	96
4.5	Limiting Attenuation at High Energy.....	98
4.6	Intermediate- and High-Energy Shielding: Hadronic Cascade.....	100
4.6.1	Hadronic Cascade from a Conceptual Standpoint	100
4.6.2	Simple One-Dimensional Cascade Model.....	101
4.6.3	Semiempirical Method: Moyer Model for a Point Source.....	103
4.6.4	Moyer Model for a Line Source	108
4.7	Use of Monte Carlo Shielding Codes for Hadronic Cascades	110
4.7.1	Examples of Results of Monte Carlo Calculations	110
4.7.2	General Comments on Monte Carlo Star-to-Dose Conversions	111
4.7.3	Shielding against Muons at Proton Accelerators	113
	Problems.....	120

5. Unique Low-Energy Prompt Radiation Phenomena	123
5.1 Introduction	123
5.2 Transmission of Photons and Neutrons through Penetrations.....	123
5.2.1 Albedo Coefficients	123
5.2.1.1 Usage of Photon Albedo Coefficients	126
5.2.2 Neutron Attenuation in Labyrinths: General Considerations	127
5.2.3 Attenuation in the First Legs of Straight Penetrations	127
5.2.4 Attenuation in Second and Successive Legs of Straight Penetrations	131
5.2.5 Attenuation in Curved Tunnels	134
5.2.6 Attenuation beyond the Exit	135
5.2.7 Determination of the Source Factor	137
5.3 Skyshine	138
5.3.1 Simple Parameterizations of Neutron Skyshine	138
5.3.2 A More Rigorous Treatment.....	140
5.3.3 Examples of Experimental Verifications	144
Problems.....	146
6. Shielding Materials and Neutron Energy Spectra	149
6.1 Introduction	149
6.2 Discussion of Shielding Materials Commonly Used at Accelerators.....	149
6.2.1 Earth	149
6.2.2 Concrete.....	151
6.2.3 Other Hydrogenous Materials.....	151
6.2.3.1 Polyethylene and Other Materials That Can Be Borated.....	151
6.2.3.2 Water, Wood, and Paraffin.....	152
6.2.4 Iron.....	152
6.2.5 High Atomic Number Materials: Lead, Tungsten, and Uranium.....	153
6.2.6 Miscellaneous Materials: Beryllium, Aluminum, and Zirconium.....	154
6.3 Neutron Energy Spectra outside of Shields	154
6.3.1 General Considerations.....	154
6.3.2 Examples of Neutron Spectra due to Incident Electrons	155
6.3.3 Examples of Neutron Spectra due to Low- and Intermediate-Energy Protons.....	155
6.3.4 Examples of Neutron Spectra due to High-Energy Protons.....	158
6.3.5 Leakage of Low-Energy Neutrons through Iron Shielding.....	160
6.3.6 Neutron Spectra due to Ions	165
6.3.7 Neutron Fluence and Dosimetry	167
7. Induced Radioactivity in Accelerator Components	169
7.1 Introduction	169
7.2 Fundamental Principles of Induced Radioactivity	169
7.3 Activation of Components at Electron Accelerators	171
7.3.1 General Phenomena	171
7.3.2 Results for Electrons at Low Energies	172
7.3.3 Results for Electrons at High Energies	174
7.4 Activation of Components at Proton and Ion Accelerators.....	177
7.4.1 General Phenomena	177

7.4.2	Methods of Systematizing Activation due to High-Energy Hadrons	181
7.4.2.1	Gollon's Rules of Thumb	188
7.4.2.2	Barbier Danger Parameter	189
7.4.3	Uniform Irradiation of Walls of an Accelerator Enclosure	195
	Problems	198
8.	Induced Radioactivity in Environmental Media	199
8.1	Introduction	199
8.2	Airborne Radioactivity	199
8.2.1	Production	199
8.2.2	Accounting for Ventilation	202
8.2.3	Propagation of Airborne Radionuclides in the Environment	203
8.2.3.1	Meteorological Considerations	203
8.2.4	Radiation Protection Standards for Airborne Radioactivity	208
8.2.4.1	Radiation Protection Standards for Occupational Workers	208
8.2.4.2	Radiation Protection Standards for Members of the Public	209
8.2.4.3	Example Numerical Values of the Derived Air Concentrations and Derived Concentration Standards	209
8.2.4.4	Mixtures of Radionuclides	212
8.2.5	Production of Airborne Radionuclides at Electron Accelerators	212
8.2.6	Production of Airborne Radionuclides at Proton Accelerators	213
8.3	Water and Geological Media Activation	214
8.3.1	Water Activation at Electron Accelerators	215
8.3.2	Water and Geological Media Activation at Proton Accelerators	216
8.3.2.1	Water Activation at Proton Accelerators	216
8.3.2.2	Geological Media Activation	216
8.3.3	Regulatory Standards	220
8.3.4	Propagation of Radionuclides through Geological Media	221
8.3.4.1	General Considerations	221
8.3.4.2	Simple Single Resident Model	222
8.3.4.3	Concentration Model	222
8.3.4.4	Example of Application: Jackson Model	225
	Problems	227
9.	Radiation Protection Instrumentation at Accelerators	229
9.1	Introduction	229
9.2	Counting Statistics	229
9.3	Special Considerations for Accelerator Environments	231
9.3.1	Large Range of Flux Densities, Absorbed Dose Rates, etc	231
9.3.2	Possible Large Instantaneous Values of Flux Densities, Absorbed Dose Rates, etc	232
9.3.3	Large Energy Domain of Neutron Radiation Fields	232
9.3.4	Presence of Mixed Radiation Fields	232
9.3.5	Directional Sensitivity	232
9.3.6	Sensitivity to Features of Accelerator Environment Other than Ionizing Radiation	232

9.4	Standard Instruments and Dosimeters	233
9.4.1	Ionization Chambers	233
9.4.2	Geiger-Müller Detectors	238
9.4.3	Thermoluminescent Dosimeters	238
9.4.4	Optically Stimulated Luminescence Dosimeters	239
9.4.5	Nuclear Track Emulsions	239
9.4.6	Track Etch Dosimeter	239
9.4.7	CR-39 Dosimeters	239
9.4.8	Bubble Detectors	240
9.5	Specialized Detectors	240
9.5.1	Thermal Neutron Detectors	240
9.5.1.1	Boron-10	241
9.5.1.2	Lithium-6	243
9.5.1.3	Helium-3	243
9.5.1.4	Cadmium	244
9.5.1.5	Silver	244
9.5.2	Moderated Neutron Detectors	244
9.5.2.1	Spherical Moderators, Bonner Spheres, and Related Detectors	245
9.5.2.2	Long Counters	253
9.5.3	Activation Detectors	255
9.5.4	Special Activation Detectors for Very High-Energy Neutrons	257
9.5.5	Proton Recoil Counters	257
9.5.6	Tissue Equivalent Proportional Chambers and Linear Energy Transfer Spectrometry	259
9.5.7	Recombination Chamber Technique	259
9.5.8	Counter Telescopes	263
	Problems	266
	Appendix: Synopses of Common Monte Carlo Codes and Examples for High-Energy Proton-Initiated Cascades	269
	References	283
	Index	295