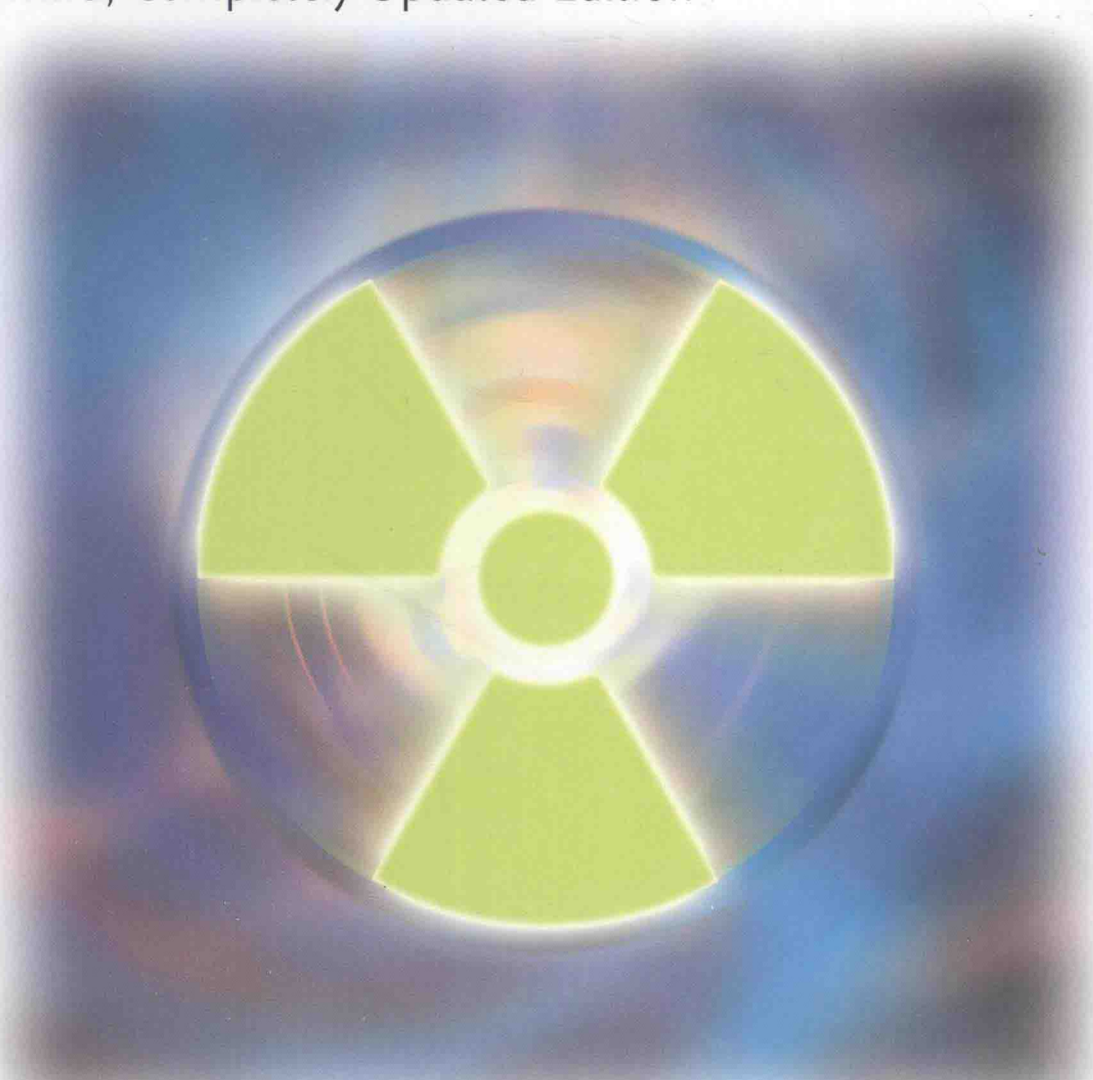
James E. Martin

WILEY-VCH

Physics for Radiation Protection

Third, Completely Updated Edition



James E. Martin

Physics for Radiation Protection

Third Completely Updated Edition

常州大学图书馆
藏书章

WILEY

WILEY-VCH Verlag GmbH & Co. KGaA

The Author

James E. Martin
2604 Bedford Road
Ann Arbour MI 48104
USA

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.:
applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

© 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Cover Design Adam-Design, Weinheim
Typesetting Kühn & Weyh, Satz und Medien, Freiburg
Printing and Binding Markono Print Media Pte Ltd, Singapore

Print ISBN: 978-3-527-41176-4
ePDF ISBN: 978-3-527-66709-3
ePub ISBN: 978-3-527-66708-6
mobi ISBN: 978-3-527-66707-9
oBook ISBN: 978-3-527-66706-2

James E. Martin

Physics for Radiation Protection

Related Titles

Turner, J. E., Downing, D. J., Bogard, J. S.

Statistical Methods in Radiation Physics

2012
ISBN: 978-3-527-41107-8

Turner, J. E.

Atoms, Radiation, and Radiation Protection

2007
ISBN: 978-3-527-40606-7

Knoll, G. F.

Radiation Detection and Measurement

2000
ISBN: 978-0-471-07338-3

Bevelacqua, J. J.

Basic Health Physics

Problems and Solutions

1999
ISBN: 978-0-471-29711-6

Bevelacqua, J. J.

Contemporary Health Physics

Problems and Solutions

1995
ISBN: 978-0-471-01801-8

Attix, F. H.

Introduction to Radiological Physics and Radiation Dosimetry

1986
ISBN: 978-0-471-01146-0

此为试读,需要完整PDF请访问: www.ertongbook.com

To the memory of

Frank A. and Virginia E. Martin
and JoAnn Martin Burkhart.

Preface

This book is the outcome of teaching radiation physics to students beginning a course of study in radiation protection, or health physics. This 3rd edition attempts as the first two did to provide in one place a comprehensive treatise of the major physics concepts required of radiation protection professionals. Numerous real-world examples and practice problems are provided to demonstrate concepts and hone skills, and even though its limited uses are thoroughly developed and explained, some familiarity with calculus would be helpful in grasping some of the subjects.

The materials in this compendium can be used in a variety of ways, both for instruction and reference. The first two chapters describe the atom as an energy system, and as such they may be of most use for those with minimal science background. Chapter 3 addresses the special condition of radioactive transformation (or disintegration) of atoms with excess energy, regardless of how acquired. Chapters 4 and 5 describe activation and fission processes and the amount of energy gained or lost due to atom changes; these define many of the sources that are addressed in radiation protection. Chapter 6 develops natural sources of radiation and radioactive materials primarily as reference material; however, the sections on radioactive dating and radon could be used as supplemental, though specialized, material to Chapter 3.

The interaction of radiation with matter and the resulting deposition of energy is covered in Chapter 7 along with the corollary subjects of radiation exposure and dose. Radiation shielding, also related to interaction processes, is described in Chapter 8 for various source geometries. Chapters 9 and 10, on internal radiation dose and environmental dispersion of radioactive materials, are also fundamental for understanding how such materials produce radiation dose inside the body and how they become available for intakes by humans. These are followed by specialty chapters on nuclear criticality (Chapter 11); radiation detection and measurement (Chapter 12); applied statistics (Chapter 13); and finally (Chapter 14) neutron sources and interactions. A course in radiation physics would likely include the material in Chapters 3, 4, 5, 7, and 8 with selections from the other chapters, all or in part, to develop needed background and to address specialty areas of interest to instructor and student. In anticipation of such uses, attempts have been made

Copyright © 2013 WILEY-VCH Verlag & Co. KGaA. Published 2013 by WILEY-VCH Verlag GmbH & Co. KGaA.

to provide comprehensive and current coverage of the material in each chapter and relevant data sets.

Health physics problems require resource data. To this end, decay schemes and associated radiation emissions are included for about 100 of the most common radionuclides encountered in radiation protection. These are developed in the detail needed for health physics uses and cross referenced to standard compendiums for straightforward use when these more in-depth listings need to be consulted. Resources are also provided on activation cross sections, fission yields, fission-product chains, photon absorption coefficients, nuclear masses, and abbreviated excerpts of the Chart of the Nuclides. These are current from the National Nuclear Data Center at Brookhaven National Laboratory; the Center and its staff are a national resource.

The units used in radiation protection have evolved over the hundred years or so that encompass the field. They continue to do so with a fairly recent, but not entirely accepted, emphasis on System Internationale (SI) Units while U.S. standards and regulations have continued to use conventional units. To the degree possible, this book uses fundamental quantities such as eV, transformations, time, distance, and the numbers of atoms or emitted particles and radiations to describe nuclear processes, primarily because they are basic to concepts being described but partially to avoid conflict between SI units and conventional ones. Both sets of units are defined as they apply to radiation protection, but in general the more fundamental parameters are used. For the specific units of radiation protection such as exposure, absorbed dose, dose equivalent, and activity, text material and examples are generally presented in conventional units because the field is very much an applied one; however, the respective SI unit is also included where feasible. By doing so, it is believed presentations are clearer and relevant to the current conditions, but it is recognized that this quandary is likely to continue.

This endeavor has been possible because of the many contributions of my research associates and students whose feedback shaped the teacher on the extent and depth of the physics materials necessary to function as a professional health physicist. I am particularly indebted to Chul Lee who began this process with me with skill and patience and to Rachael Nelson who provided invaluable help in capping off this 3rd edition. I hope it helps all who undertake study in this exciting field to appreciate how physics underpins it.

In an undertaking of this scope, it is inevitable that undetected mistakes creep in and remain despite the best efforts of preparers and editors; thus, reports (jemartin@umich.edu) of errors found would be appreciated.

James E. Martin, Ph.D., CHP
Associate Professor (emeritus) of
Radiological Health
The University of Michigan, 2012

Contents

Preface *XVII*

1 **Structure of Atoms** *1*
1.1 Atom Constituents *2*
1.2 Structure, Identity, and Stability of Atoms *5*
1.3 Chart of the Nuclides *6*
1.4 Nuclear Models *8*
Problems – Chapter 1 *9*

2 **Atoms and Energy** *11*
2.1 Atom Measures *12*
2.2 Energy Concepts for Atoms *14*
2.2.1 Mass-energy *15*
2.2.2 Binding Energy of Nuclei *16*
2.3 Summary *18*
Other Suggested Sources *18*
Problems – Chapter 2 *19*

3 **Radioactive Transformation** *21*
3.1 Processes of Radioactive Transformation *21*
3.1.1 Transformation of Neutron-rich Radioactive Nuclei *23*
3.1.2 Double Beta ($\beta\beta$) Transformation *27*
3.1.3 Transformation of Proton-rich Nuclei *27*
3.1.4 Positron Emission *29*
3.1.5 Average Energy of Negatron and Positron Emitters *32*
3.1.6 Electron Capture (EC) *33*
3.1.7 Radioactive Transformation of Heavy Nuclei by Alpha Particle Emission *35*
3.1.8 Theory of Alpha Particle Transformation *38*
3.1.9 Transuranic (TRU) Radionuclides *40*
3.1.10 Gamma Emission *41*
3.1.11 Internal Transition (Metastable or Isomeric States) *42*
3.1.12 Internal Conversion *43*

Physics for Radiation Protection, Third Edition. James E. Martin
Copyright © 2013 WILEY-VCH Verlag & Co. KGaA. Published 2013 by WILEY-VCH Verlag GmbH & Co. KGaA.

3.1.13 Multiple Modes of Radioactive Transformation *49*
3.1.14 Transformation by Delayed Neutron Emission *51*
3.1.15 Transformation by Spontaneous Fission *51*
3.1.16 Proton Emission *53*
3.2 Decay Schemes *54*
3.3 Rate of Radioactive Transformation *57*
3.3.1 Activity *58*
3.3.2 Units of Radioactive Transformation *58*
3.3.3 Mathematics of Radioactive Transformation *60*
3.3.4 Half-Life *62*
3.3.5 Mean Life *63*
3.3.6 Effective Half-life *64*
3.4 Radioactivity Calculations *65*
3.4.1 Half-life Determination *68*
3.5 Activity–mass Relationships *70*
3.5.1 Specific Activity *70*
3.6 Radioactive Series Transformation *73*
3.6.1 Series Decay Calculations *73*
3.6.2 Recursive Kinetics: the Bateman Equations *76*
3.7 Radioactive Equilibrium *77*
3.7.1 Secular Equilibrium *78*
3.7.2 Transient Equilibrium *80*
3.7.3 Radionuclide Generators *81*
3.8 Total Number of Transformations (Uses of τ and λ_{Eff}) *84*
3.9 Discovery of the Neutrino *86*
Acknowledgments *87*
Other Suggested Sources *87*
Problems – Chapter 3 *88*

4 Interactions *91*
4.1 Production of X-rays *91*
4.2 Characteristic X-rays *93*
4.2.1 X-rays and Atomic Structure *95*
4.2.2 Auger Electrons *96*
4.3 Nuclear Interactions *98*
4.3.1 Cross-Section *100*
4.3.2 *Q*-values for Nuclear Reactions *102*
4.4 Alpha Particle Interactions *104*
4.4.1 Alpha–Neutron Reactions *105*
4.5 Transmutation by Protons and Deuterons *106*
4.5.1 Proton–Alpha Particle (p,α) Reactions *108*
4.5.2 Proton–Neutron (p,n) Reactions *109*
4.5.3 Proton–Gamma (p,γ) Reactions *110*
4.5.4 Proton–Deuteron Reactions *110*
4.5.5 Deuteron–Alpha (d,α) Reactions *111*

此为试读，需要完整PDF请访问：www.ertongbook.com

4.5.6 Deuteron–Proton (d,p) and Deuteron–Neutron (d,n) Reactions *111*
4.6 Neutron Interactions *114*
4.6.1 Radiative Capture (n,γ) Reactions *114*
4.6.2 Charged Particle Emission (CPE) *115*
4.6.3 Neutron–Proton (n,p) Reactions *116*
4.6.4 Neutron–Neutron (n,2n) Reactions *116*
4.7 Activation Product Calculations *117*
4.7.1 Neutron Activation Product Calculations *119*
4.7.2 Charged Particles Calculations *124*
4.8 Medical Isotope Reactions *126*
4.9 Transuranium Elements *128*
4.10 Photon Interactions *130*
4.10.1 Activation by Photons *130*
4.11 Fission and Fusion Reactions *133*
4.11.1 Fission *133*
4.11.2 Fusion *134*
4.12 Summary *138*
Other Suggested Sources *139*
Problems – Chapter 4 *139*

5 Nuclear Fission and its Products *143*
5.1 Fission Energy *145*
5.2 Physics of Sustained Nuclear Fission *147*
5.3 Neutron Economy and Reactivity *152*
5.4 Nuclear Power Reactors *154*
5.4.1 Reactor Design: Basic Systems *155*
5.5 Light Water Reactors (LWRs) *157*
5.5.1 Pressurized Water Reactor (PWR) *157*
5.5.2 Boiling Water Reactor (BWR) *159*
5.5.3 Inherent Safety Features of LWRs *161*
5.5.4 Decay Heat in Power Reactors *163*
5.5.5 Uranium Enrichment *164*
5.6 Heavy Water Reactors (HWRs) *165*
5.6.1 HWR Safety Systems *168*
5.7 Breeder Reactors *169*
5.7.1 Liquid Metal Fast Breeder Reactor (LMFBR) *171*
5.8 Gas-cooled Reactors *174*
5.8.1 High-temperature Gas Reactor (HTGR) *175*
5.9 Reactor Radioactivity *176*
5.9.1 Fuel Cladding *177*
5.9.2 Radioactive Products of Fission *178*
5.9.3 Production of Individual Fission Products *182*
5.9.4 Fission Products in Spent Fuel *184*
5.9.5 Fission Product Poisons *185*
5.10 Radioactivity in Reactors *188*

5.10.1 Activation Products in Nuclear Reactors 188
5.10.2 Tritium Production in Reactors 191
5.10.3 Low-level Radioactive Waste 192
5.11 Summary 193
Acknowledgments 194
Other Suggested Sources 195
Problems – Chapter 5 195

6 Naturally Occurring Radiation and Radioactivity 197
6.1 Discovery and Interpretation 197
6.2 Background Radiation 199
6.3 Cosmic Radiation 200
6.4 Cosmogenic Radionuclides 203
6.5 Naturally Radioacitve Series 207
6.5.1 Neptunium Series Radionuclides 214
6.6 Singly Occurring Primordial Radionuclides 214
6.7 Radioactive Ores and Byproducts 216
6.7.1 Resource Recovery 218
6.7.2 Uranium Ores 218
6.7.3 Water Treatment Sludge 219
6.7.4 Phosphate Industry Wastes 219
6.7.5 Elemental Phosphorus 220
6.7.6 Manhattan Project Wastes 221
6.7.7 Thorium Ores 223
6.8 Radioactivity Dating 224
6.8.1 Carbon Dating 224
6.8.2 Dating by Primordial Radionuclides 225
6.8.3 Potassium–Argon Dating 226
6.8.4 Ionium (^{230}Th) Method 227
6.8.5 Lead-210 Dating 227
6.9 Radon and its Progeny 228
6.9.1 Radon Subseries 229
6.9.2 Working Level for Radon Progeny 232
6.9.3 Measurement of Radon 236
6.10 Summary 240
Acknowledgements 241
Other Suggested Sources 241
Problems – Chapter 6 242

7 Interactions of Radiation with Matter 245
7.1 Radiation Dose and Units 245
7.1.1 Radiation Absorbed Dose 246
7.1.2 Radiation Dose Equivalent 246
7.1.3 Radiation Exposure 247
7.2 Radiation Dose Calculations 249

7.2.1 Inverse Square Law *249*
7.3 Interaction Processes *250*
7.4 Interactions of Alpha Particles and Heavy Nuclei *252*
7.4.1 Recoil Nuclei and Fission Fragments *254*
7.4.2 Range of Alpha Particles *254*
7.5 Beta Particle Interactions and Dose *257*
7.5.1 Energy Loss by Ionization *258*
7.5.2 Energy Losses by Bremsstrahlung *258*
7.5.3 Cerenkov Radiation *259*
7.5.4 Attenuation of Beta Particles *261*
7.5.5 Range Versus Energy of Beta Particles *262*
7.5.6 Radiation Dose from Beta Particles *264*
7.5.7 Beta Dose from Contaminated Surfaces *267*
7.5.8 Beta Contamination on Skin or Clothing *268*
7.5.9 Beta Dose from Hot Particles *269*
7.6 Photon Interactions *270*
7.6.1 Photoelectric Interactions *271*
7.6.2 Compton Interactions *272*
7.6.3 Pair Production *274*
7.6.4 Photodisintegration *276*
7.7 Photon Attenuation and Absorption *277*
7.7.1 Attenuation (μ) and Energy Absorption (μ_{En}) Coefficients *280*
7.7.2 Effect of E and Z on Photon Attenuation/Absorption *284*
7.7.3 Absorption Edges *286*
Checkpoints *288*
7.8 Energy Transfer and Absorption by Photons *288*
7.8.1 Electronic Equilibrium *293*
7.8.2 Bragg–Gray Theory *295*
7.9 Exposure/Dose Calculations *296*
7.9.1 Point Sources *297*
7.9.2 Gamma Ray Constant, Γ *298*
7.9.3 Exposure and Absorbed Dose *300*
7.9.4 Exposure, Kerma, and Absorbed Dose *301*
7.10 Summary *303*
Acknowledgments *303*
Other Suggested Sources *304*
Problems – Chapter 7 *304*

8 Radiation Shielding *307*
8.1 Shielding of Alpha-Emitting Sources *307*
8.2 Shielding of Beta-Emitting Sources *308*
8.2.1 Attenuation of Beta Particles *308*
8.2.2 Bremsstrahlung Effects for Beta Shielding *311*
8.3 Shielding of Photon Sources *314*
8.3.1 Shielding of Good Geometry Photon Sources *315*

8.3.2 Half-Value and Tenth-Value Layers *322*
8.3.3 Shielding of Poor Geometry Photon Sources *324*
8.3.4 Use of Buildup Factors *330*
8.3.5 Effect of Buildup on Shield Thickness *331*
8.3.6 Mathematical Formulations of the Buildup Factor *333*
8.4 Gamma Flux for Distributed Sources *338*
8.4.1 Line Sources *339*
8.4.2 Ring Sources *341*
8.4.3 Disc and Planar Sources *342*
8.4.4 Shield Designs for Area Sources *343*
8.4.5 Gamma Exposure from Thick Slabs *350*
8.4.6 Volume Sources *355*
8.4.7 Buildup Factors for Layered Absorbers *356*
8.5 Shielding of Protons and Light Ions *357*
8.6 Summary *360*
Acknowledgments *360*
Other Suggested Sources *361*
Problems – Chapter 8 *361*

9 Internal Radiation Dose *365*
9.1 Absorbed Dose in Tissue *365*
9.2 Accumulated Dose *366*
9.2.1 Internal Dose: Medical Uses *369*
Checkpoints *369*
9.3 Factors In The Internal Dose Equation *370*
9.3.1 The Dose Reciprocity Theorem *377*
9.3.2 Deposition and Clearance Data *378*
9.3.3 Multicompartment Retention *378*
9.4 Radiation Dose from Radionuclide Intakes *383*
9.4.1 Risk-Based Radiation Standards *384*
9.4.2 Committed Effective Dose Equivalent (CEDE) *385*
9.4.3 Biokinetic Models: Risk-Based Internal Dosimetry *386*
9.4.4 Radiation Doses Due to Inhaled Radionuclides *388*
9.4.5 Radiation Doses Due to Ingested Radionuclides *398*
9.5 Operational Determinations of Internal Dose *405*
9.5.1 Submersion Dose *406*
Checkpoints *406*
9.6 Tritium: a Special Case *408*
9.6.1 Bioassay of Tritium: a Special Case *410*
9.7 Summary *411*
Other Suggested Sources *412*
Problems – Chapter 9 *412*

10 Environmental Dispersion *415*
10.1 Atmospheric Dispersion *417*

10.1.1 Atmospheric Stability Effects on Dispersion 420
10.1.2 Atmospheric Stability Classes 422
10.1.3 Calculational Procedure: Uniform Stability Conditions 424
10.1.4 Distance x_{max} of Maximum Concentration (χ_{max}) 426
10.1.5 Stack Effects 427
Checkpoints 429
10.2 Nonuniform turbulence: Fumigation, Building Effects 429
10.2.1 Fumigation 429
10.2.2 Dispersion for an Elevated Receptor 431
10.2.3 Building Wake Effects: Mechanical Turbulence 432
10.2.4 Concentrations of Effluents in Building Wakes 433
10.2.5 Ground-level Area Sources 435
10.2.6 Effect of Mechanical Turbulence on Far-field Diffusion 436
10.3 Puff Releases 438
10.4 Sector-Averaged χ/Q Values 439
10.5 Deposition/Depletion: Guassian Plumes 443
10.5.1 Dry Deposition 443
10.5.2 Air Concentration Due to Resuspension 447
10.5.3 Wet Deposition 449
10.6 Summary 452
Other Suggested Sources 452
Problems – Chapter 10 453

11 Nuclear Criticality 455
11.1 Nuclear Reactors and Criticality 456
11.1.1 Three Mile Island Accident 456
11.1.2 Chernobyl Accident 458
11.1.3 NRX Reactor: Chalk River, Ontario, December 1952 461
11.1.4 SL-1 Accident 461
11.1.5 K-reactor, Savannah River Site, 1988 462
11.1.6 Fukushima-Daichi Plant—Japan, March 11, 2011 463
11.2 Nuclear Explosions 464
11.2.1 Fission Weapons 464
11.2.2 Fusion Weapons 465
11.2.3 Products of Nuclear Explosions 466
11.2.4 Fission Product Activity and Exposure 467
Checkpoints 469
11.3 Criticality Accidents 470
11.3.1 Y-12 Plant, Oak Ridge National Laboratory, TN: June 16, 1958 470
11.3.2 Los Alamos Scientific Laboratory, NM: December 30, 1958 471
11.3.3 Idaho Chemical Processing Plant: October 16, 1959, January 25, 1961, and October 17, 1978 472
11.3.4 Hanford Recuplex Plant: April 7, 1962 473
11.3.5 Wood River Junction RI: July 24, 1964 473
11.3.6 UKAEA Windscale Works, UK: August 24, 1970 474

11.3.7 Bare and Reflected Metal Assemblies *474*
11.4 Radiation Exposures in Criticality Events *475*
11.5 Criticality Safety *476*
11.5.1 Criticality Safety Parameters *478*
11.6 Fission Product Release in Criticality Events *482*
11.6.1 Fast Fission in Criticality Events *483*
11.7 Summary *485*
Acknowledgments *486*
Other Suggested Sources *486*
Problems – Chapter 11 *486*

12 Radiation Detection and Measurement *489*
12.1 Gas-Filled Detectors *489*
12.2 Crystalline Detectors/Spectrometers *493*
12.3 Semiconducting Detectors *494*
12.4 Gamma Spectroscopy *495*
12.4.1 Gamma-Ray Spectra: $h\nu \leq 1.022$ MeV *495*
12.4.2 Gamma-Ray Spectra: $h\nu \geq 1.022$ MeV *500*
12.4.3 Escape Peaks and Sum Peaks *502*
12.4.4 Gamma Spectroscopy of Positron Emitters *503*
12.5 Portable Field Instruments *504*
12.5.1 Geiger Counters *504*
12.5.2 Ion Chambers *505*
12.5.3 Microrem Meters *506*
12.5.4 Alpha Radiation Monitoring *506*
12.5.5 Beta Radiation Surveys *507*
12.5.6 Removable Radioactive Surface Contamination *508*
12.5.7 Instrument Calibration *509*
12.6 Personnel Dosimeters *509*
12.6.1 Film Badges *509*
12.6.2 Thermoluminescence Dosimeters (TLDs) *510*
12.6.3 Pocket Dosimeters *511*
12.7 Laboratory Instruments *511*
12.7.1 Liquid Scintillation Analysis *511*
12.7.2 Proportional Counters *515*
12.7.3 End-window GM Counters *517*
12.7.4 Surface Barrier Detectors *518*
12.7.5 Range Versus Energy of Beta Particles *519*
Other Suggested Sources *520*
Problems – Chapter 12 *521*

此为试读，需要完整PDF请访问：www.ertongbook.com