



principles of radiological health

PRINCIPLES OF RADIOLOGICAL HEALTH

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PREFACE

The principles of radiological health are applied by the engineer or the health physicist to provide a healthful environment for people living in the nuclear age. This text is an outgrowth of the authors' recent experiences in classroom teaching, practical field applications, and advanced research. Thirty-five years of combined experience by the authors in teaching graduate radiological health courses, special radiation protection courses for engineers, scientists, and practicing physicians, and consulting in both radiation protection and radioactive waste management have provided the necessary basis for a definitive treatment of radiation protection and radioactive wastes management.

This basic textbook presents the problems and applications approach toward radiation safety. The specific premise underlying the book is that the practitioner should be able to measure the radiation exposure and/or dosage; to evaluate the hazards from the radiation; to design control methods, equipment, and procedures; to institute the controls; and to check the effectiveness of the measures initiated.

In order to be able to perform these actions effectively, one needs to have certain background information and theory. It is the authors' belief that no other book in existence fills the need of a text which prepares the engineer or other technical person to carry out these functions.

The first three chapters introduce the reader to nuclear reactions and the resultant energy releases. Chapter 4 lays the groundwork for interactions of radiations with matter, an understanding which is requisite for satisfactory measurements and evaluation of radiation effects. Chapter 5 defines the nomenclature and methodology for specifying radiation dosages. Formulas and their applications for calculating radiation dose for varying geometries, types of radiations, and modes of bodily intake are presented in a readily usable form.

The next three chapters are concerned with measurement of radiation. All current radiation measurement techniques are described. Successful

measurements are those which are made with the minimum effort necessary to obtain the desired accuracy. Accomplishing this task requires a knowledge of not only the radiation measurement methods but also the principles and statistics of such measurements. The treatment of statistics is brief, but it includes example problems covering the full range of counting statistics.

Evaluations of radiation hazards are made from dosages and effects data derived from texts and incidental exposure experiences. Radiation effects include physical, chemical, and biological—all of these are described in Chapter 9.

The subject of environmental transport, Chapter 10, is developed around the three spheres of man's environment, namely, air, water, and soil. The movement of radionuclides through the environment deals with their continual uptake and release by specific chemical, physical, and biological processes.

Chapter 11, Radiation Protection Methods, provides a practical treatment of the subject matter. The breadth of coverage is wide ranging and includes topics from laboratory procedures to detailed shielding analyses.

The area of wastes management, the topic of Chapter 12, considers the various aspects of handling, treating, and disposal for liquid, solid, and gaseous wastes. Information is provided on the present practices of storage, concentration, and containment of high-level and intermediate-level wastes, as well as the dilution to the environment of low-level wastes. Descriptions are included of the various methods of offgas handling, containerization, and ultimate storage. Ways of dissipating waste heat generated by decaying radionuclides are also discussed.

Today X rays are the major source of ionizing radiation exposure to the population. Consequently, a detailed chapter on X rays is included. In Chapter 13, the subjects treated are (a) generation, (b) usage, (c) exposure, and (d) shielding. This information is particularly applicable for X-ray technicians, public health workers, and various professionals.

Nonionizing radiations are causing increased concern. Increasingly powerful sources such as radar and lasers are presenting new and potential health hazards. This topic is introduced in Chapter 14, because the principles of control are closely related to those for ionizing radiation. Recent legislation has treated these two subjects together and an introduction to this text is justified.

Ionizing radiation is an integral part of modern science and technology. The use of nuclear energy in modern industry is of considerable importance today, but the major impact is still to come. Man's daily experiences with

ionizing radiation, whether through medicine, engineering applications, or scientific research, will increase. While the nuclear power industry is expected to increase a hundredfold by the year 2000, the acceptance of ionizing radiation to drive chemical reactions must not be underestimated.

Those of us engaged in teaching and research have observed the development and growth of problems associated with radiological health. The need for a textbook emphasizing radiological health principles, particularly as these basic concepts can be used in modern technology, is apparent. Similarly, there is an obvious need for a useful reference source which illustrates the practical problems of ionizing radiation control.

Acknowledgments are extended to those many students who have assisted in the development of this text.

Austin, Texas

Earnest F. Gloyna
Joe O. Ledbetter

CONTENTS

PREFACE	vii
Chapter 1 Atomic Structure	1
1-1. Historical Concepts	1
1-2. Periodic Table of the Elements	3
1-3. Nuclides and Isotopes	4
1-4. Orbital Electrons	6
1-5. Nuclear Properties	9
1-6. Summary	15
Problems	16
Bibliography	16
Chapter 2 Radioactive Processes	17
2-1. Extranuclear Atomic Forces	17
2-2. Nuclear Reactions	21
2-3. Fission	24
2-4. Fusion	28
2-5. Radioactivity	29
2-6. Radioactive Decay	35
Problems	39
Bibliography	40
Chapter 3 Radiological Reaction Times	41
3-1. Fluctuations in Activity	41
3-2. Radioactive Decay Rate	41

3-3. Radioactive Half-Life	43
3-4. Biological and Effective Half-Lives	45
3-5. Mean Lifetime	45
3-6. Nuclide Determination by Decay Rate	46
3-7. Specifying Sample Activity	50
3-8. Nonexponential Decay	51
3-9. Radioactive Decay as a Measure of Time	53
Problems	53
Bibliography	54
 Chapter 4 Interaction of Radiation with Matter	 55
4-1. Introduction to Interaction	55
4-2. Specific Ionization	57
4-3. Heavy Charged Particles	57
4-4. Electron Absorption	64
4-5. Gamma-Ray and X-Ray Absorption	69
4-6. Interaction of Neutrons with Matter	75
4-7. Summary	79
Problems	80
Bibliography	81
 Chapter 5 Radiation Dosage	 83
5-1. Ionization Basis of Dosimetry	83
5-2. Units of Radiation Dose	84
5-3. Effect of Source Geometry	87
5-4. Calculation of Dosage from External Sources	89
5-5. Calculation of Dosage from Internal Sources	94
5-6. Critical Organ and Body Burden	96
5-7. Radiation Protection Guides	96
5-8. Maximum Permissible Doses	97
5-9. Calculation of MPC Values	97
5-10. Effective Energy for MPC Calculations	100
5-11. MPC Calculations for Radionuclide Mixtures	106
5-12. Summary	107
Problems	108
Bibliography	108
 Chapter 6 Principles of Detection	 109
6-1. Collection of Ions	109
6-2. Instruments of the Ionization Region	111
6-3. Proportional Detection	114

6-4. Geiger-Mueller Detection	115
6-5. Scintillation Detection	117
6-6. Semiconductor Detection	119
6-7. Chemical Detection	120
6-8. Cloud, Bubble, and Spark Chambers	120
6-9. Detection of Heat Produced	121
6-10. Summary	121
Problems	122
Bibliography	122
Chapter 7 Statistics of Radiation Measurement	123
7-1. Statistical Distributions	123
7-2. Applications of Counting Statistics	127
7-3. Graphical Analysis	133
7-4. Ion-Current Statistics	134
7-5. Sampling Statistics	134
7-6. Summary	136
Problems	136
Bibliography	137
Chapter 8 Techniques of Measurement	139
8-1. Statistical Accuracy Required	139
8-2. Gas-Flow Counting	140
8-3. Window versus Internal Counting	141
8-4. Geometry	141
8-5. Counts Lost in Counter	144
8-6. Self-Absorption	146
8-7. Absolute Counting	148
8-8. Plateaus	150
8-9. Counter Assemblies	151
8-10. Range Measurements	154
8-11. Energy Measurement	156
8-12. Half-Life Determination	160
8-13. Separating Types of Radiations	161
8-14. Identifying Radionuclides	161
8-15. Neutron Counting	162
8-16. Activation Analysis	163
8-17. Personal Dosimetry	164
8-18. Tissue-Equivalent Measurements	166
8-19. Lowering Background	166
8-20. Survey Meters	167
8-21. Summary	169

Problems	170
Bibliography	170
Chapter 9 Effects of Ionizing Radiations	173
9-1. Absorption of Energy	173
PART I. EFFECTS ON SOLIDS	175
9-2. Displacements, Replacements, and Changed Atoms	175
9-3. Bond Rupture and Free Radicals	176
9-4. Storage and Release of Energy	176
9-5. Changes in Physical Properties	177
9-6. Changes in Chemical Properties	179
PART II. EFFECT ON LIQUIDS AND GASES	179
9-7. Efficiency of Change	179
9-8. Free-Radical Formation	180
9-9. Reaction Rates	181
9-10. Direct and Indirect Actions	182
9-11. Dissociation and Main-Chain Scission	183
9-12. Polymerization and Cross-Linkage	184
9-13. Oxidation and Reduction	185
PART III. EFFECTS ON BIOLOGICAL SYSTEMS	186
9-14. LET and RBE Concepts	186
9-15. Immediate and Delayed Effects	187
9-16. Rate of Growth	187
9-17. Length of Life	188
9-18. Mutations	190
9-19. Carcinogenesis	192
9-20. Cataract Formation, Skin Burns, and Loss of Hair	193
9-21. Relative Biological Sensitivity	194
9-22. Theories of Mechanism for Damage	195
9-23. Target Theory and Number of Hits per Change	196
9-24. Oxygen Enhancement of Injury	198
9-25. Radiomimetic Chemicals	198
9-26. Chemical Protection	199
9-27. Reparable and Irreparable Injury	199
9-28. Acute Radiation Syndrome	201
9-29. Human Experience	203
PART IV. APPLICATIONS	204
9-30. Physical Effects	205
9-31. Chemical Effects	205
9-32. Biological Effects	207
9-33. Summary	208
Problems	209
Bibliography	210

Chapter 10 Environmental Transport of Radionuclides	213
10-1. Ecosystem Effects	213
PART I. IN THE ATMOSPHERE	214
10-2. Winds	214
10-3. Stability	217
10-4. Atmospheric Dispersion	218
10-5. Deposition of Airborne Radioactivity	231
10-6. Application of Atmospheric Dispersion Formulas	233
PART II. IN THE GEOSPHERE	234
10-7. Cation Exchange by Clay Minerals	234
10-8. Soil, Sediment, and Plant Reactions	241
10-9. Disposal of Gaseous Wastes into Porous Formations	243
10-10. Fate of Injected Liquids	245
PART III. IN THE HYDROSPHERE	251
10-11. General Effects of Wastewater Discharges	252
10-12. Dispersion Characteristics	257
10-13. Inland Waterways	260
10-14. Estuarine and Coastal Characteristics	270
10-15. Oceanic Characteristics	275
10-16. Summary	277
Problems	278
Bibliography	279
 Chapter 11 Radiation Protection Methods	 285
11-1. Basic Principles	285
11-2. Dose Regulations	286
11-3. Radiation Monitoring	286
11-4. Control of Source Emissions	287
11-5. Time of Exposure	287
11-6. Handling and Containment of Radioisotopes	288
11-7. Decontamination	289
11-8. Distance from Source	290
PART I. SHIELDING	292
11-9. Basic Concepts	292
11-10. Principles of Shielding	293
11-11. Calculation of Radiation Transmission	295
11-12. Exponential Attenuation	295
11-13. Relaxation Length and Half-Value Layer	297
11-14. Narrow-Beam and Broad-Beam Radiations	298
11-15. Buildup Factor	299

11-16. Geometry Considerations	303
11-17. Shielding Materials	307
PART II. SHIELDING APPLICATIONS	308
11-18. Portable Source Shields	308
11-19. Cobalt Therapy Devices	310
11-20. X-Ray Machines	313
11-21. Storage Chambers	313
11-22. Hot Cell Windows	316
11-23. Reactor Shielding	317
11-24. Shielding of Radioactive Wastes	321
11-25. Low-Level-Counting Shielding	321
11-26. Backscattering and Air Scattering	323
11-27. Summary	329
Problems	330
Bibliography	331
 Chapter 12 Radioactive Wastes Management	 333
12-1. Classification of Radioactive Wastes	333
12-2. Sources and Amounts	334
12-3. Reactor Fuel Reprocessing	340
PART I. CONCENTRATION OF SOLIDS	347
12-4. Baling	347
12-5. Incineration	347
12-6. Decontamination Wastes	348
PART II. CONCENTRATION OF LIQUIDS	349
12-7. Evaporation	349
12-8. Calcination	352
12-9. Precipitation	355
12-10. Ion Exchange and Adsorption	355
12-11. Solvent Extraction	359
12-12. Foam Separation	360
12-13. Biological Uptake	360
PART III. CONCENTRATION OF GASES	361
12-14. Adsorption	361
12-15. Absorption	362
12-16. Condensation and Liquefaction	362
12-17. Pressurization	363
PART IV. CONCENTRATION OF AEROSOLS	363
12-18. Filtration	363
12-19. Centrifugation	368

CONTENTS

xvii

12-20. Scrubbing	368
12-21. Electrostatic Precipitation	368
PART V. FIXATION	369
12-22. Concreting	369
12-23. Asphaltic Insolubilization	370
12-24. Vitrification	371
12-25. Encapsulation	374
PART VI. DISPOSITION	375
12-26. Containment for Decay	375
12-27. Heat Generation	380
12-28. Ground Disposal	382
12-29. Water Disposal	383
12-30. Air Disposal	385
12-31. Isotopic Change	387
12-32. Reclamation of Wastes	387
12-33. Summary	388
Problems	389
Bibliography	389
Chapter 13 X Rays	393
13-1. Milestones in X-Ray Development	393
13-2. Potential Sources of Exposure	395
13-3. Nature and Source of X Rays	396
13-4. Production of X Rays	399
13-5. Interaction of X Rays with Matter	401
13-6. Medical X-Ray Equipment	404
13-7. Inspection Criteria	407
13-8. Protective Barriers	408
13-9. Construction Details	417
Problems	417
Bibliography	418
Chapter 14 Hazards of Nonionizing Radiations	421
14-1. Ultraviolet Radiation	421
14-2. Visible Radiation	423
14-3. Infrared Radiation	424
14-4. Microwave Radiation	425
14-5. Longer Wavelengths	427
14-6. Measurement	427
14-7. Summary	428
Problems	428
Bibliography	429

Appendix A	Abbreviations and Constants	431
Appendix B	Values of Exponential Functions	433
Appendix C	Effective Half-Lives	435
Appendix D	Bases of Dose Calculations for the Standard Man	437
Appendix E	MPC Values for Air and Water	441
Appendix F	Decay Information for Selected Radionuclides	457
AUTHOR INDEX		459
SUBJECT INDEX		465

CHAPTER 1 ATOMIC STRUCTURE

The atom may be viewed as having two principal parts—the extremely dense nucleus and the electron field that surrounds the nucleus. Each of these provides the basis for a whole, complex area of study. Nuclear physicists and chemists are concerned with the characteristics of the nucleus and its parts, while the study of the electron field has moved beyond the determination of chemical valence to quantum mechanical considerations. By definition the *atom* is the smallest unit of an element which exhibits all the chemical properties of the element.

1-1. Historical Concepts

Many scientific and philosophical hurdles had to be overcome before the atomic-molecular theory of structure was generally accepted. The concept of matter and atoms can be traced to antiquity; however, the nuclear concept was introduced by Rutherford only within this century.

The early Greek philosophers sought to develop a connection between their philosophies on matter, being, and becoming, and the material world. Democritus and his teacher Leucippus in the fifth century B.C. postulated that all matter was composed of very small, but finite, particles that could not be cut, *atomos*. Democritus' theories went even further and described compounds. However, owing to the strong influence of the mistaken beliefs of Aristotle, the atomic-molecular theory was dormant for 2000 years. The natural atomic sciences began to develop along the lines that they are known today after chemist and physicist Robert Boyle (1627–1691) produced his theories on the behavior and composition of

gases. Through these efforts and those of Bacon, Newton, and others, the theories of Democritus finally prevailed. Then Lavoisier, the acknowledged "father of chemistry," interpreted the process of combustion. Richter (1792) and Dalton (1803) proposed the ideas that chemical elements always combine in definite quantitative proportions to give compounds. Dalton's atoms were followed by Avogadro's molecules (1811). Avogadro maintained that, at the same temperature and pressure, equal volumes of all gases contained the same number of molecules. The relationships between Avogadro's number (N_a) and mass are shown by

$$N_a = 6.025 \times 10^{23} \text{ atoms/gram atomic weight}$$

$$\text{(also molecules/gram molecular weight)} \quad (1-1)$$

and a term defined as the atomic mass unit (amu)†:

$$\text{amu} = (1/N_a) \text{ g} = 1.66 \times 10^{-24} \text{ g} \quad (1-2)$$

Using Dalton's concepts, Berzelius turned to laboratory experimentation to establish combining weights which he believed to be atomic weights. He changed the basis of atomic weights from hydrogen equal to 1, as Dalton used, to oxygen equal to 16, because oxygen is more reactive than hydrogen. Berzelius furthered the concept of valence in chemical bonds and started the shorthand element and compound notation that is used today. Another step toward understanding the atom was made by Faraday (1791–1867), who proved that there is a relationship between the amount of substance transformed electrically and the amount of electricity required to induce the transformation. This relation is now known to be 96,514 coulombs (C) per gram mole equivalent, Faraday's constant (F_a); e.g., a sodium chloride solution would liberate 1 g mole of sodium (univalent) at the cathode for each 96,514 C of electricity applied.

Advances made by Maxwell, Clausius, and Boltzmann showed that gases did indeed consist of molecules in rapid motion, as Boyle had postulated. In 1865 Loschmidt determined the approximate size of molecules and the number present in 1 cm³ of gas. A more nearly accurate size of about 10⁻⁸ cm for the diameter of an atom was set by Lord Kelvin in 1870, but Loschmidt had shown the way. The very small size of the atom may be better illustrated by stating that 10 million atoms placed in a line would extend only 1 mm.

Shortly prior to 1900, the work of Hittorf and J. J. Thomson led to the conclusion that the atomistic behavior of an ionic charge varies only in

† For complete information regarding abbreviations, see Appendix A.

multiples of a basic unit, indicating that the charge is carried by some kind of indivisible particle. Several years before, Stoney had suggested the name *electron* for the elementary unit of electrical charge and the term was adopted for the particle. Of considerable importance is the fact that electrons are always associated with the same mass of 9.107×10^{-28} g (when at rest). The significance of the electron to an overall understanding of the atom is illustrated by pointing out that conventional chemistry and atomic physics are primarily studies of the behavior of electrons with respect to atoms.

Millikan showed by measuring the terminal settling velocities of oil drops in different electrical fields (1911) that the electric charge in atoms really does occur only in multiples of an elementary unit (ϵ).

$$\begin{aligned}\epsilon &= \frac{F_a}{N_a} = \frac{(96,514 \text{ C/gmole equivalent})}{6.025 \times 10^{23} \text{ molecules/gmole}} \\ &= 1.60 \times 10^{-19} \text{ C} = 4.80 \times 10^{-10} \text{ electrostatic units (esu)} \quad (1-3)\end{aligned}$$

Oil droplets suspended in an electric field make possible the equating of the gravitational force ($m \cdot g$) with the electrical force ($q \cdot E$); i.e.,

$$\text{force} = m \cdot g = q \cdot E \quad (1-4)$$

where m = mass

g = acceleration of gravity

q = total charge on drop = number of electrons $\times \epsilon$

E = electrical field strength (potential/distance)

The movement of a charged particle across an electrical potential also forms the basis for defining the elemental unit of energy used in radiological health—the *electron volt* (eV). An electron volt is the amount of energy gained by an electron moving across a potential of 1 V, as shown in Fig. 1-1.

1-2. Periodic Table of the Elements

Although Döbereiner and others had noted a relationship between the chemical properties of atoms and their atomic weights as early as 1829, it remained for Mendeleev to systematize this connection into the periodic law in 1870, a law which states that the properties of the elements are periodic functions of their atomic weights. Mendeleev was so confident in his scheme that he left blanks for some undiscovered elements and claimed that some of the measured atomic weights were in error—he was