TABLE OF CONTENTS

Preface ......................................................... v

1 Radiation and Radioactivity ........................... 1
   1.1 Historical Review of the Nature of Matter 1
   1.2 Radioactivity ........................................ 8
   1.3 Characteristics of Commonly used Radionuclides 17
   1.4 Radiation Quantities and Units .................. 18

2 Biological Effects of Radiation ...................... 21
   2.1 History of Biological Effects ..................... 21
   2.2 Cellular Damage and Possible Cellular Processes 22
   2.3 Biological Effects .................................. 26
   2.4 Internal Radiation Exposure ....................... 29
   2.5 Irradiation During Pregnancy ...................... 30
   2.6 Biological Hazards from Radioactive Compounds 31
   2.7 Radiation Risk Assessment ......................... 31
   2.8 Radiation Exposure Risks .......................... 33

3 Radiation Protection Standards ..................... 37
   3.1 Background to Current Standards ................. 37
   3.2 Natural and Man-made Background Radiation Levels 38
   3.3 Regulation of Radiation ........................... 39
   3.4 NRC Licenses ...................................... 42
   3.5 10 CFR Part 20 (Standards for Protection Against Radiation) 43
   3.6 UW-Madison License and Regulations ............. 47

4 Radiation Safety Principles ......................... 51
   4.1 Time ............................................... 51
   4.2 Distance .......................................... 51
   4.3 Shielding .......................................... 51
   4.4 Practical Application ............................. 55
   4.5 Housekeeping ..................................... 56

5 Radioactive Material Work Practices ............... 57
   5.1 Ordering and Receiving Procedures ............. 57
   5.2 Inventories ....................................... 57
   5.3 Disposal of Radioactive Material ................ 58
   5.4 Laboratory Surveys and Allowable Contamination Levels 65
   5.5 Exceptions ....................................... 67
   5.6 Radionuclides and Uses with Special Requirements 68

6 Emergency Procedures and Decontamination ......... 83
   6.1 General Procedures ............................... 83
   6.2 Personnel Overexposures and Contamination Injuries 85
   6.3 Personnel Decontamination Procedures .......... 85
   6.4 Laboratory and Equipment Decontamination .... 86
   6.5 Cautions ........................................... 88

7 Radiation Detection and Measurement ............... 89
   7.1 Radiation Detectors ................................ 89
   7.2 Radiation Dosimeters ............................ 89
   7.3 Gas-Filled Radiation Detectors .................. 92
   7.4 Scintillation Detectors ......................... 99
   7.5 Radiation Detection and Measurement Techniques 100
   7.6 Liquid Scintillation Counter (LSC) ............. 103
   7.7 Removable Contamination Wipe Survey Techniques 114
   7.8 Counting Statistics ................................ 116
8 Transportation of Radioactive Materials
8.1 Hazardous Materials Regulations 127
8.2 Radioactive Materials Transportation Definitions 131
8.3 General Requirements for Preparing Radioactive Materials for Transport 133
8.4 Shipping Limited Quantity of Radioactive Material -- a Special Category 135
8.5 Shipping Radioactive Material via a Commercial Carrier (e.g., FedEx, DHL) 136
8.6 Emergency Response 138
8.7 Receipt of Radioactive Material 139

9 Irradiator and Nuclear Gauges
9.1 Types of Irradiators 145
9.2 Self-contained Irradiators 146
9.3 Irradiator Regulations and License Conditions 150
9.4 Nuclear Gauges 151
9.5 X-ray Fluorescence (XRF) 156

10 Analytical and Medical X-rays
10.1 X-ray Sources 157
10.2 Hazards of X-rays 157
10.3 Radiation Protection Techniques 158
10.4 Electron Microscopes 159
10.5 Analytical X-ray Systems 160
10.6 Diagnostic X-rays 162
10.7 X-ray Regulations 168

11 Nuclear Reactors
11.1 Basic Physics of Nuclear Reactors 169
11.2 Neutron Cycle 172
11.3 Reactor Design and Radiation Hazards 173
11.4 Reactor Classification 175
11.5 Power Reactors 177
11.6 UW Research Reactor 178

12 Particle Accelerators
12.1 Historical Developments 181
12.2 Particle Accelerator Components 182
12.3 Low Energy Accelerators 183
12.4 High Energy Accelerators 186
12.5 Ion Implantation 187
12.6 Accelerators at the University of Wisconsin 190
12.7 Radiation Protection at Particle Accelerators 191

13 Radiation in Medicine
13.1 Nuclear Medicine 193
13.2 Radiopharmaceutical Therapy 201
13.3 Clinical Lab Procedures (RIA) 204
13.4 Brachytherapy 204
13.5 External Beam Therapy (Teletherapy) 208
13.6 Veterinary Radiation Medicine Programs 211

14 Radioactive Waste
14.1 Consequences of Releases of Radioactivity 215
14.2 Solid Waste 217
14.3 Liquid Waste 218
14.4 Atmospheric Release 220
14.5 Decommissioning 227
### Laser Safety
15.1 Characteristics and Components  
15.2 Terms and Definitions  
15.3 Hazard Classification  
15.4 Biological Effects  
15.5 Laboratory Controls  
15.6 Protective Eye Wear  
15.7 Laser Dyes  
15.8 Associated Laser System Hazards  
15.9 Safety Audits and Laser Safety Tips

### UV Radiation Safety
16.1 Physical / Health Effects  
16.2 Protective Measures  
16.3 Practical Hazard Assessment and Control

### Electromagnetic Radiation
17.1 Radiofrequency (RF) and Microwave Radiation  
17.2 Extremely Low Frequency (ELF) Radiation

### LABORATORY EXERCISES
1 Radiation Detection and Measurement  
   Radioactive Decay  
   Portable Survey Meters  
   Liquid Scintillation Counters (LSC)
2 UW Radiation Safety Program  
   Ordering and Receipt of Radioactive Materials  
   Use of Radioactive Material  
   Disposal of Radioactive Waste  
   Survey Techniques and Decontamination

### UW RADIATION SAFETY REGULATIONS
   Administration  
   Radionuclide Authorizations  
   How to Obtain Radionuclides  
   Facilities for Use and Storage of Radionuclides  
   Training and Instruction for Radiation Workers  
   Dosimetry / Personnel Monitoring  
   Laboratory Surveys and Contamination  
   Radionuclide Procedures with Special Requirements  
   Transportation and Shipment of Radioactive Materials  
   Emergency Procedures  
   Disposal of Radioactive Waste  
   Radiation Safety ALARA Audits  
   Location of Necessary Forms

### APPENDICES
A Glossary
B-1 Instruction Concerning Prenatal Radiation Exposure (Rev. 3) 323
Questions and Answers Concerning Prenatal Radiation Exposure 325
Form Letter for Declaring Pregnancy 328
B-2 Instruction Concerning Prenatal Radiation Exposure (Draft Rev. 3) 329
Instructions Concerning Pregnant Women 329
Making the Decision to Declare Pregnancy 332
How to Declare your Pregnancy 333
Steps to Lower Radiation Dose 333
Additional Information 334
Form Letter for Declaring Pregnancy 334
B-3 Instruction Concerning Prenatal Radiation Exposure (Rev. 2) 335
Effects on the Embryo/Fetus of Exposure to Radiation & Other Environmental Hazards 337
Possible Health Risks to Children of Women who are Exposed to Radiation during Pregnancy 337
NRC Position 337
Radiation Dose Limits 338
Advice for Employee and Employer 338
Internal Hazards 338
B-4 Instruction Concerning Risks from Occupational Radiation Exposure 339
C Sample Radiation Work Forms 351
NRC Form 3 352
Radionuclide Facility Survey 354
Radioactive Waste Disposal Guidelines 355
Radioactive Waste Disposal Form 357
State of Wisconsin Notice to Employees Form 359
Radioactive Liquid Waste Tag and Radioactive - LSA Label 360
Aqueous Radioactive Waste (carboy) Tag and Flammable Hazardous Waste (carboy) Tag 360
HAZMAT Shipping Paper 361
Radioactive Labels (I, II, III) 362
Radioactive Animal Waste Disposal 362
D Instruction for Dosimeter Application 364
Dose Estimate for Lost Radiation Dosimeter 365
Application for Personnel Dosimeter 366
E Sample Radiation Safety Quiz 367
F Answers to Chapter Review Questions 371

INDEX 373
PREFACE

This manual is written for the individual who anticipates working with or around sources of ionizing radiation or small amounts of radioactive materials in a research setting at the University of Wisconsin - Madison. It provides the radiation worker with basic information needed to protect himself/herself and others (i.e., non-radiation workers), and to understand and comply with Federal, State, and University regulations regarding the use of radioactive materials or radiation-producing machines at the University of Wisconsin - Madison. It is designed for a wide spectrum of individuals including physicians, researchers, technicians, and workers who work in areas where radioactive materials or radiation producing devices are being used.

Based upon responsibilities, certain radiation workers are required to have extensive training and experience in radiation physics and radiation-induced effects. These persons are usually principal investigators, lab managers supervising radiation work or individuals working in laboratories where large quantities of radioactive materials are used. Before becoming a principal investigator or supervisor, the Nuclear Regulatory Commission (NRC) requires a radiation worker to have received a minimum of 40 hours formal instruction in the nature, detection, and biological hazards of radioactivity; measures effective in reducing radiation exposure; and current radiation and radioactive materials regulations. This manual is not addressed to these individuals nor will it wholly satisfy the training and experience requirements to become a radiation laboratory supervisor or principal investigator. However, for the large number of radiation workers who require basic radiation protection training or who have minimal experience in these subjects, this manual, in conjunction with the lecture and laboratory training blocks, will be sufficient to provide the basic radiation safety procedures needed to safely function in a radiation work environment.

For principal investigators and persons who will handle radioactive materials daily, this manual and the successful completion of the Radiation Safety training block are required before being allowed to work with radioactive materials. The training is a four-hour block of instruction which is designed to: (1) reinforce the contents of this manual, (2) provide an understanding of the operations and limitations of various types of radiation monitoring and detection systems, (3) present suggested forms and procedures needed to properly document a radiation program, and (4) assess the worker's comprehension of radiation safety with a multiple-choice quiz. Principal investigators / laboratory managers should call or eMail the Safety Department (or go to the Radiation Safety Annex in Rm. B62 Biochemistry) and ask for a Radiation Safety for Radiation Workers manual for their new workers. The training class is held weekly at varying times and consists of a 1-hour lecture, a 2-hour demonstration/laboratory, and a 1-hour open-book, multiple-choice exam. The training class is not meant as a substitute for prior reading of this manual, rather it (i.e., Chapters 1, 2, 6, Labs 1 and 2) is designed to complement the manual. It is likely that some workers will be unable to pass the exam without having studied this manual beforehand. The examination answer sheet is used by the Safety Department to document that a worker has achieved the basic knowledge of radiation and radiation safety to enable them to work, not just around, but with radiation sources. Thus, successful completion of the examination will allow workers to work with radiation sources or with small amounts of radioactive materials in clinical and research laboratory settings.

Although there is often an implied distinction between Radiation Worker¹, Laboratory Worker², Medical Worker³ and X-ray Worker⁴, all nonmedical personnel who work with radiation sources (e.g., ³H, ³²P, analytic x-ray, veterinary x-ray, etc.) and require monitoring must successfully complete this training program. Because medical radiation workers normally require extensive training for certification and students enrolled in a numbered course are required to receive training specific to the classroom hazards involved, they are exempt from this training requirement at that particular work-site. Because researchers' workers often move from one laboratory to another with different hazards involved, and, once they receive dosimetry there is no mechanism to assess training, this training is targeted to them.

This manual has 17 chapters, 2 laboratories, and 5 appendices which are divided into 7 basic sections. At the end of each chapter and throughout the labs, there are a series of questions which are useful as a self-check on your

¹Radiation workers are persons who will work for a principal investigator and will handle radioactive material daily.
²Laboratory workers include persons who work in or frequent laboratories or areas where radioactivity is used or stored, but do not work directly with radioactive materials, and workers who handle lab ware and equipment that may have been used in radiation work.
³Medical workers are persons who perform clinical work with radioactive materials or radiation.
⁴X-ray workers are persons who only work with nonmedical, machine produced radiation (e.g., x-ray diffraction, electron microscopy, veterinary and research x-ray machines) and have no contact with radioactive materials.
level of understanding the information. These questions are to gage your understanding of the material. Therefore, if you are unsure of the correct answer, review that portion of the chapter before leaving the question. The information presented can be summarized as:

- **Chapters 1 - 4** contain the basic instructional material found in NRC Regulatory Guide 8.29, *Instruction Concerning Risks from Occupational Radiation Exposure* (Appendix B-3). The NRC requires radiation instruction to include basic radiation terminology, biological effects of radiation, summaries of pertinent regulations, and radiation safety work procedures.

- **Chapters 5, 6, and 7** contain information about working safely with radioactive materials. Chapter 5 is a summary of the radiation safety program at the UW. It describes ordering and inventory requirements, waste disposal options, radiation surveys, and uses requiring additional considerations. Chapter 6 discusses emergency procedures and Chapter 7 discusses detection and measurement of radioactivity, focusing on GM and LSC systems as well as survey procedures.

- **Chapters 8 and 9** are specialized chapters included in this manual to meet specific training needs. Chapter 8, Transportation of Radioactive Materials provides some basic information that workers should review prior to becoming certified in transportation of radioactive material. Chapter 9, Irradiators and Nuclear Gauges, is meant to be read by workers prior to attending the special training offered by Safety to enable them to use one of the closed-beam irradiators on campus or a nuclear moisture/density gauge off campus.

- **Chapters 10, 11, 12, 13, 14, 15, 16 and 17** are informational chapters which describe other sources of radiation commonly encountered on the UW campus. Chapter 10, Analytical and Medical X-rays; Chapter 11, Nuclear Reactors; Chapter 12, Particle Accelerators; Chapter 13, Radiation in Medicine; Chapter 14, Radioactive Waste; Chapter 15, Laser Safety; Chapter 16, UV Radiation Safety; and Chapter 17, Electromagnetic Radiation. These are included for completeness. Each of these pertains to other types of radiation sources used on campus and personnel directly working with any of these sources are normally required to receive special training from the owner of the system. Thus, these may be used to familiarize the employee or layman with each topic.

- **Laboratories 1 and 2** are demonstrations of some basic radiation detection (Lab 1) and record keeping concepts (Lab 2), including suggested forms and formats. Laboratory 1 is a summary of Chapter 7 as it pertains to beta detection and measurement. Laboratory 2 describes the radiation safety program at the UW and the requisite record keeping. It is extracted from Chapter 5.

- **UW Radiation Safety Regulations** are included in this booklet. Much of the booklet contains radiation safety program requirements (e.g., Chapter 5 and Lab 2 discuss the radiation safety program, including waste and surveys), having a separate book for regulations was redundant. This section references where to find the needed information throughout the booklet.

- **Appendices** expand on information contained in the main body of the manual. Appendix A is a glossary of selected radiation safety words and phrases, other chapters contain definitions of specialized terms. Appendix B are extracts of various NRC Regulatory Guides. Appendix B-1, B-2 and B-3 are several versions of NRC Regulatory Guide 8.13, *Instruction Concerning Prenatal Radiation Exposure*. We include older versions of the guide because the information presented is valid and useful to the pregnant worker. Appendix B-4 is the revised NRC Regulatory Guide 8.29, *Instruction Concerning Risks from Occupational Radiation Exposure*. Appendixes C and D contain example forms used in radiation safety. Appendix E is a sampling of questions used to make up the radiation safety quiz. Appendix F has the correct answers to chapter and lab questions, but not the quiz found in Appendix E.

Because familiarity often leads to callousness, workers should review this manual periodically (e.g., every two to three years, or so) to be kept abreast of changing requirements and to refresh their memory of proper safety procedures. If you routinely work with more than one millicurie of radioactive material or if you supervise workers who use these quantities, you should have a more thorough understanding of radiation safety and mandated work procedures than is presented in this manual. The Radiation Safety Office can provide short, training classes tailored to your specific safety needs. Please contact either your supervisor or the Safety Office to schedule such training.