CONTEMPORARY HEALTH PHYSICS

Problems and Solutions

JOSEPH JOHN BEVELACQUA
Wisconsin Electric Power Company

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Cover Picture
View of a living brain as seen with MRI (Magnetic Resonance Imaging).
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This book is dedicated to my wife, Terry. Her love and understanding have been of great assistance to the completion of this text.

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PREFACE

This book contains over 375 problems in health physics and discusses their practical applications. It assumes that the reader is familar with the science of radiation protection and is either an active participant in that field or interested in learning more about the health physics profession. In particular, this text is particularly useful to individuals preparing for the American Board of Health Physics Certification Examination.

The first part of this book provides an overview of the scientific basis for the field of health physics. The reader is provided with a comprehensive set of references supplemented by appendices that outline selected concepts required to fully appreciate the specialized Part II material. Over 130 problems and their solutions are provided to permit the reader to demonstrate a sound knowledge of health physics fundamentals. The problems are set within scenarios that are intended to enhance the reader's existing knowledge by demonstrating the basic principles in complex situations requiring a sound knowledge of both theoretical health physics principles and good judgment.

Part II provides the reader with examples of the concepts and calculations frequently encountered in the various fields of health physics. Chapter titles are selected to loosely conform to the various subfields of the health physics profession—that is, medical, university, fuel cycle, power reactor, environmental, and accelerator health physics. The problems are intended to illustrate general concepts within the framework of specific areas such as medical or power reactor health physics.

In addition to illustrating the fundamental concepts of health physics, the collection includes a large number of detailed problems that are often encountered by the radiation protection professional. Some of these problems involve considerable effort, whereas others are more simplistic and can be solved from

traditional lectures in health physics. In addition, there are problems which address topics not usually covered in existing texts. These problems are not presented as isolated bits of health physics knowledge, but are introduced within a scenario that stimulates an integrated professional approach to the problem. Professional judgment and sound health physics principles are emphasized.

The third part of this book provides the solutions to the problems presented in the first and second parts. Many of these are worked in considerable detail to further illustrate and emphasize the concepts introduced in Parts I and II.

The present collection of problems is largely based upon the American Board of Health Physics Comprehensive Examination. The author was privileged to serve 4 years as a member, Vice-Chairman, and Chairman of the ABHP Comprehensive Panel of Examiners. The experience gained in the development of this examination and the weaknesses of candidates attempting this examination have affected the content of this work.

The author is deeply indebted to the members of the examination panels and the ABHP Board for their professional interaction which greatly expanded the author's own health physics knowledge. The opinions and interpretations reflected in this work are the author's and do not necessarily reflect those of his current or previous employers.

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A NOTE ON UNITS

In the United States many regulations, most reporting requirements, and a large portion of practicing health physicists utilize traditional units (Ci, R, rad, rem, etc.). The use of traditional units is currently in conflict with much of the international community and scientific publications which have adopted the SI system (Bq, C/kg, Gy, Sv, etc.).

This book adopts a set of units that are commonly utilized in practical health physics applications. These traditional units are selected because they are what the practicing health physicist will most frequently encounter in daily assignments and they can be easily related to their SI counterparts. Traditional units are also utilized to ensure that communications between the health physicist and the health physics technician are clearly understood. When SI units are utilized to convey ICRP dose limit recommendations or criteria, their traditional counterparts are also provided.

The conflict of units will remain until the United States adopts the SI system in its regulations. This should be done over a period of years in order to ensure that all health physicists are thoroughly familiar and comfortable with the SI units.

For those readers that feel more comfortable with the SI system, the following conversion factors are provided:

SI Unit	Traditional Unit
Bq	2.70×10^{-11} Ci
Gy	100 rad
C/kg of air	3881 R
Sv	100 rem

As the reader can quickly note the choice of units is more a matter of familiarity rather than scientific rigor. By using these simple factors, the reader should begin to feel more comfortable with either set of units.

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CONTENTS

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PART I

BASIC CONCEPTS: THEORY AND PROBLEMS

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1

INTRODUCTION

Health physics or radiation protection is the science dealing with the protection of radiation workers and the general public from the harmful effects of radiation. Health physicists work in a variety of environments, including medical facilities, universities, accelerator complexes, power reactors, and fuel cycle facilities. The health physicist is responsible for the radiological safety aspects of facility equipment and services. Radiological assessments of plant equipment, facility modifications, design changes, employee exposures, or the assessment of radiological effluents are key functions of a health physicist.

The fundamental tools of the health physicist include the fields of mechanics, electricity and magnetism, energy transfer, and quantum mechanics. Atomic and nuclear structure, radioactive transformations, and the interaction of radiation with matter are the cornerstones of health physics knowledge. Application of these fundamental tools permits the health physicist to measure, quantify, and control radiation exposures to affected groups.

Introductory health physics texts typically cover these topics in several hundred pages. Because the scope of this text builds upon these fundamental concepts, we will not repeat them herein. The reader is referred to the texts listed as references to this chapter for a discussion of health physics fundamentals. We will, however, provide several appendices that illustrate selected fundamental concepts. Also included is an extensive set of scenarios, including over 130 worked examples, that illustrate the fundamental concepts and permit the reader to assess his or her knowledge of these concepts. Because the fundamentals are needed to fully understand the remaining chapters in this text, a review of the scenarios in this chapter is recommended.

SCENARIOS

Scenario 1

One of your neighbors, while digging up his back yard to build a pool, has discovered some old planks. Another neighbor, who has been investigating the possibility of the existence of a Viking settlement in the area, believes that the planks may be significant. He wishes to conduct an archeological expedition prior to any further construction. You offer to carbon date the wood to help settle the argument.

1.1. Carbon dating is possible because:
   a. The specific activity of carbon-14 in living organisms has changed over time, and one can identify the era of time the organism lived based on its current specific activity.
   b. Carbon-14 is in secular equilibrium with its daughter.
   c. The specific activity of carbon-14 in living organisms is relatively constant through time, but decays after the death of the organism.
   d. The specific activity of carbon-14 in wood increases over time due to shrinkage of the wood.

1.2. Calculate the approximate age of the wood given the following:

C-14 $T_{1/2}$ = 5600 years

Specific activity for C-14 in a nearby living tree
$= 1.67 \times 10^{-1}$ Bq/g

Specific activity for C-14 in the old wooden plank
$= 1.50 \times 10^{-1}$ Bq/g

Scenario 2

A nearby hospital has received a shipment of a Mo-99 generator. The shipment contained 1000 mCi of Mo-99 when manufactured. It arrived at the hospital 48 h after its production.

The decay scheme is illustrated in Fig. 1.1.

1.3. If the generator is milked exactly upon arrival at the hospital, how much Tc-99m will be obtained? Assume that 95% of the available Tc-99m is eluted.

1.4. If the generator is milked 24 hr after the initial milking, how much Tc-99m will be obtained?

Scenario 3

Consider a parent radioisotope A ($T_{1/2}$ = 10 hr) that decays to a daughter radioisotope B ($T_{1/2}$ = 1 hr).

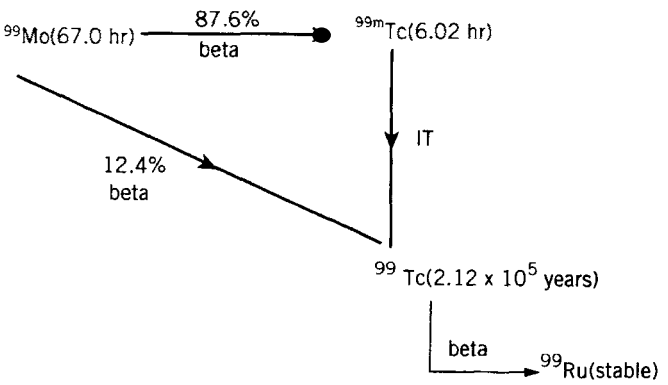

Fig. 1.1 Decay scheme for Mo-99.

1.5. Which of the following statements is true concerning these radioisotopes?
   a. Because $\lambda_A > \lambda_B$, the parent and daughter will eventually reach the condition of transient equilibrium.
   b. Because $\lambda_A >> \lambda_B$, the parent and daughter will eventually reach the condition of secular equilibrium.
   c. Because $\lambda_A = \lambda_B$, no state of equilibrium can ever exist between the parent and daughter.
   d. Because $\lambda_B > \lambda_A$, the parent and daughter will eventually reach the condition of transient equilibrium.
   e. Because $\lambda_B >> \lambda_A$, the parent and daughter will eventually reach the condition of secular equilibrium.

1.6. Assuming that the activity of the daughter is zero at time zero, at what time (t) will the daughter reach its maximum activity?

Scenario 4

The plant manager at your facility has requested that you review the following questions and provide the best solution. These questions will be used to assess the qualification of health physics candidates for entry-level positions in your facility's radiological controls department.

1.7. Tissue dose from thermal neutrons arises principally as a result of:
   a. (n, γ) reactions with hydrogen
   b. (n, γ) reactions with hydrogen and (n, p) reactions with nitrogen
   c. (n, p) reactions with carbon
   d. (n, α) reactions with carbon
   e. (n, α) reactions with carbon and (n, γ) reactions with hydrogen

1.8. Tissue dose from fast neutrons (0.1 to 14 MeV) is due principally to:
   a. Resonance scattering with nuclei
   b. Inelastic scattering with nuclei
   c. Coulomb scattering with nuclei
   d. Nuclear capture and spallation
   e. Elastic scattering with nuclei

1.9. The most probable process for energy deposition by a 1-MeV photon in tissue is:
   a. Photoelectric absorption
   b. Pair production
   c. Compton scattering
   d. Photonuclear absorption
   e. Bremsstrahlung

1.10. The principal mechanism of dose deposition by a 5-MeV alpha particle that stops in tissue is:
   a. Inelastic scattering by atomic electrons
   b. Elastic scattering by atomic electrons
   c. Elastic scattering by atomic nuclei
   d. Inelastic scattering by atomic nuclei
   e. Nuclear spallation

1.11. The principal mechanism of dose deposition by a 100-keV beta particle that stops in tissue is:
   a. Elastic scattering by atomic electrons
   b. Elastic scattering by atomic nuclei
   c. Inelastic scattering by atomic nuclei
   d. Inelastic scattering by atomic electrons
   e. Bremsstrahlung

1.12. The average number of ion pairs produced by a 100-keV beta particle that stops in air is approximately:
   a. 300
   b. 30
   c. 30,000
   d. 3000
   e. 300,000.

1.13. The average number of ion pairs produced by a 100-keV beta particle that stops in a germanium semiconductor is:
   a. 30,000
   b. 30
   c. 300

d. 3000
e. 300,000

1.14 A nuclide that undergoes orbital electron capture:
a. Emits an electron, a neutrino, and the characteristic x-rays of the daughter.
b. Emits a neutrino and the characteristic x-rays of the daughter.
c. Also decays by positron emission.
d. Also emits internal conversion electrons.
e. Makes an isomeric transition.

1.15. The specific gamma-ray emission rate for Cs-137 in units of R hr^{-1} Ci^{-1} m^2 is approximately:
a. 1.3
b. 0.12
c. 0.33
d. 0.05
e. 0.77

1.16. An example of an organ or tissue for which the Annual Limit on Intake (ALI) is determined by the limit for nonstochastic effects is the:
a. Red bone marrow
b. Gonads
c. Lung
d. Breast
e. Thyroid

Scenario 5

The radioisotope I-126 (atomic number 53) can decay into stable Te-126 (atomic number 52) by orbital electron capture (EC) or by positron emission. It can, alternatively, decay by negative beta emission into stable Xe-126 (atomic number 54). The fractions of the transformations that take place via these modes are: EC 55%, positron emission 1%, and beta decay 44%. An I-126 source also emits gamma photons of energy 386 keV and 667 keV as well as characteristic x-rays of Te. The energy equivalents (Δ) of the mass excesses of the atoms involved in these transformations are (Δ = atomic mass − atomic mass number):

Atom	Δ (MeV)
Te-126	−90.05
I-126	−87.90
Xe-126	−89.15

The energy equivalent of the electron rest mass is 0.511 MeV, and the binding energy of the K-shell electron in I-126 is 32 keV.
For the following questions, choose the best answer.

1.17. The energy released (Q-value) by the decay of I-126 via capture of a K-shell electron, going directly to the ground state of Te-126, is:
   a. 0.03 MeV
   b. 1.13 MeV
   c. 2.12 MeV
   d. 2.15 MeV
   e. 2.18 MeV

1.18. The energy released (Q-value) by the decay of I-126 via position emission to the ground state of Te-126 is:
   a. 0.51 MeV
   b. 1.02 MeV
   c. 1.13 MeV
   d. 1.64 MeV
   e. 2.15 MeV

1.19. The energy released in the decay of I-126 to the ground state of Xe-126 by beta emission is:
   a. 0.20 MeV
   b. 0.23 MeV
   c. 0.90 MeV
   d. 0.74 MeV
   e. 1.25 MeV

1.20. Of the following kinds of radiation emitted from I-126, which is the single least significant potential contributor to internal dose?
   a. Annihilation photons
   b. Bremsstrahlung
   c. Internal-conversion electrons
   d. Auger electrons
   e. Antineutrino

   How would your answer change if external dose contributions were under consideration?

1.21. Why are the 32-keV Te x-rays present with an I-126 source?
   a. The nucleus of Te-126 has excess energy after the EC event. This excess energy is released by Te-126 as x-rays.
   b. Stable Te-126 has excess energy after the positron emission. This excess energy is released by Te-126 as x-rays.
   c. Electrons rearranging between the L and M shells produce x-rays.

d. Te x-rays are released when the EC event creates a vacancy in the inner shells, and electrons from outer shells fill the vacancy.
e. Te x-rays are equivalent to the bremsstrahlung radiation emitted by I-126.

Scenario 6

The nuclide Sr-90 (atomic number 38) decays by beta emission into Y-90 (atomic number 39), which then decays by beta emission into Zr-90 (atomic number 40), with the half-lives noted below:

$$\text{Sr-90} \xrightarrow[27.7 \text{ years}]{} \text{Y-90} \xrightarrow[64.2 \text{ hr}]{} \text{Zr-90}$$

1.22. What is the mean, or average, lifetime of a Y-90 atom?
a. 31.1 hr
b. 44.5 hr
c. 77.04 hr
d. 92.6 hr
e. 128.4 hr

1.23. What is the specific activity of Y-90 in SI units?
a. 5.42×10^5 Bq/kg
b. 7.22×10^{16} Bq/kg
c. 2.01×10^{19} Bq/kg
d. 7.22×10^{19} Bq/kg
e. 6.49×10^{21} Bq/kg

1.24. Starting with a pure Sr-90 sample at time $t = 0$, a researcher finds that the Y-90 activity is 3.4 mCi at $t = 72.0$ hours. What was the activity of the Sr-90 at $t = 0$?
a. 1.84 mCi
b. 3.40 mCi
c. 4.37 mCi
d. 6.29 mCi
e. 7.39 mCi

Scenario 7

You have been asked to assist in the technical evaluation of an ionization chamber and environmental sampling results. Your boss has requested answers to the following questions. Assume the density of air at STP $\approx 1.293 \times 10^{-6}$ kg/cm^3.

1.25. A free air ionization chamber shows a flow of electrical charge of 1×10^{-9} A. The chamber has a sensitive volume of 4 cm^3. The reading is taken at 10°C and 755 mm Hg. Find the exposure rate in R/sec based on STP conditions.

1.26. You are asked to provide immediate, on-site measurement results for a series of environmental samples that are being collected every 100 min. It has been requested that each sample count be preceded by a background count. From past experience, you estimate that the net sample and background counting rates should be approximately 2400 and 300 cpm, respectively. Assuming that each sample must be analyzed before the next one is received, how long would you count the sample to minimize the standard deviation estimate for the sample's net activity?

1.27. A water sample that was counted for 10 min yielded 600 counts. A 40-min background count yielded a background rate of 56 cpm. At a 95% confidence level (one-tail test), determine whether or not there was any net activity in the sample.

Scenario 8

You are responsible for operating the counting room at a nuclear facility. You need to minimize the counting time required for air samples because of the heavy workload and a need to streamline operations in the count room. The bulk of your air sample workload is counting I-131. The following parameters are applicable to your operation:

Counting efficiency = 20%

Background count time = sample count time

Background count rate = 50 cpm

Sampling flow rate = 5 liters/min

Sample collection time = 10 min

Iodine collection efficiency = 70%

MPC for iodine = 1×10^{-9} $\mu Ci/cm^3$

1.28. Calculate the minimum sample and background counting time required to ensure an LLD at the 95% confidence level less than or equal to 0.10 MPC for I-131.

1.29. List methods that could be used in the field or in the counting room to reduce the time required to process I-131 samples. Explain how each method reduces processing time.

Scenario 9

As a health physicist at a nuclear facility, you are asked to develop a program to characterize the radioactive particulate emissions through the facility's main ventilation stack. The following questions relate to various aspects of this assignment.

1.30. In designing the sampling system, you have determined that the stack internal diameter is 0.5 m and the volumetric flow through the stack is 20 m^3/min. You want to use a vacuum source which will provide a constant volumetric flow of 200 liters/min through your sampling train. Assuming laminar flow, what should the internal diameter of the sampling nozzle be to ensure isokinetic sampling conditions?

1.31. To ensure that your sample is representative of laminar flow conditions (nonturbulent, constant velocity) within the stack, discuss factors that you should consider relative to the location of your sampling nozzle within the stack.

1.32. You have decided to use filtration techniques to capture your sample and are evaluating three types of media (cellulose, glass-fiber, and membrane filters). List advantages and disadvantages of each.

Scenario 10

You are responsible for a high-volume air sampler located downwind from a Department of Energy (DOE) facility following a suspected release of Pu-239. The air sampler has a calibrated volumetric flow rate of 55 SCFM, and the filter has an alpha self-absorption factor and filter collection efficiency of 0.4 and 0.8, respectively. The air sampler is operated at this flow rate for 1 hr, and the filter surface is measured with a gross alpha probe detector having an active detection area of 60 cm^2 and a background count of 20 counts in 100 min. The detector efficiency for alpha is 0.3 cpm/dpm, and the active filter area is 500 cm^2. Assume that the filter face velocity is uniform.

Data

Half-Life for Pu-239 = 24,390 years

Alpha yield = 100%

LLD(95%) = 4.66 sb (where sb is the standard deviation of the background)

1.33. The initial filter-face alpha count immediately after the 1 hr sampling period was 2000 for a 10-min counting interval. Forty-eight hours later, the same filter is measured again with the same detector, and

the count was 220 in 100 min. Explain why the count rate is lower 48 hr later.

1.34. What is Pu-239 airborne activity (in dpm/m^3) and the standard deviation for this measured quantity?

1.35. What is the lower limit of detection (LLD) at the 95% confidence level for this air sampling and detection system (in dpm/m^3) for the same sampling conditions?

Scenario 11

This scenario deals with the working-level unit.

With the passage of the Radon Control Act of 1988, the Environmental Protection Agency (EPA) is now instructed by the Congress to assess public risks of radon exposure in public buildings (including schools) throughout the nation. Regarding the measurement, detection, and health physics of radon-222 and its daughter products, answer the following questions:

1.36. Historically, an operational definition of the working-level exposure unit (WL) for radon-222 daughters has been 100 pCi/liter of each short-lived daughter product in secular equilibrium. Using this definition and the data provided derive the total alpha energy per liter of air (MeV/liter) associated with a concentration of one working level. Radon and its short-lived daughters include:

Nuclide	Alpha Energy (MeV)	Half-life
Radon-222	5.49	3.82 days
Polonium-218	6.00	3.05 min
Lead-214	0	26.8 min
Bismuth-214	0	19.7 min
Polonium-214	7.68	1×10^{-6} min

1.37. Using the data provided, calculate the concentration of radon-222 gas in air determined from a single-count, filter collection method for radon daughters. Assume a 50% equilibrium between radon-222 and its daughters. Neglect special considerations for radioactive growth and decay during sampling and counting. The following data are provided:

Sample collection period = 5 min

Counting time = 1 min

Total alpha counts = 230

Counting efficiency = 0.3

Pump flow rate = 10 liters/min

Conversion factor = 150 dpm alpha $liter^{-1}$ WL^{-1}

1.38. List common methods for the detection and measurement of radon and/or its daughters for use in assessing public exposure in building structures.

Scenario 12

A common type of portable beta–gamma survey instrument uses an air ionization chamber vented to atmospheric pressure. The cylindrical detector is 3 in. high and 3 in. in diameter with a 7-mg/cm^2 beta window and a 400-mg/cm^2 beta shield. The side walls are 600 mg/cm^2. Answer the following questions with respect to the instrument's response versus the "true" dose rates specifically associated with the following conditions.

1.39. Briefly describe a potential source of error associated with measuring gamma and beta dose rates while moving in and out of a noble gas environment.

1.40. List and briefly explain two harsh environmental conditions which could have an adverse effect on the accuracy of the instrument response while in the area.

1.41. Briefly describe the most significant source of error associated with measuring true beta and gamma surface dose rates from contact measurements of small sources.

1.42. Briefly explain a source of error associated with measuring beta dose rates from large-area sources, with each source comprised of a different radionuclide.

1.43. Briefly describe a source of error associated with measuring beta dose rates from high-energy beta sources using open minus closed window readings.

Scenario 13

ANSI N13.11-1983, "American National Standard for Dosimetry—Personal Dosimetry Performance Criteria for Testing," is used as a basis for testing the performance of suppliers of dosimetry services. This standard provides criteria for testing personnel dosimetry performance for any type of dosimeter whose reading is used to provide a lifetime cumulative personal radiation record. The test procedure in this standard evaluates the absorbed dose and dose equivalent at two irradiation depths (0.007 cm and 1.0 cm). The radiation sources used for the performance tests are Cs-137, Sr-90/Y-90, heavy water moderated Cf-252, and an x-ray machine. The x-ray machine is used to generate several photon beams with average energies between 20 keV and 70 keV. Choose the single answer which is most correct.

1.44. The provisions of this standard apply:
   a. to neither pocket dosimeters nor extremity dosimeters.
   b. to pocket dosimeters but not to extremity dosimeters.
   c. only to beta and gamma radiation.
   d. to extremity dosimeters but not to pocket dosimeters.
   e. to film badges but not to thermoluminescent dosimeters (TLDs).

1.45. Because of the particular irradiation depths chosen for the tests, a dosimetry system which is calibrated with the standard tests may be reporting doses which are different than the actual dose received. For which of the following tissues (red bone marrow, skin, gonads, lens of the eye, or whole body) is this difference most significant?

1.46. Because of the particular radiation sources specified, the standard least adequately tests for radiations emitted by:
   a. C-14, power reactor leakage neutrons
   b. P-32, Cf-252
   c. Y-90/Sr-90, Am–Be source
   d. Co-60, Ni-65
   e. Uranium slab, Cf-252

1.47. A dosimeter of a processor who has passed the test category for:
   a. beta radiation is appropriate for measuring low-energy photons.
   b. beta radiation is not appropriate for measuring beta radiation from all sources.
   c. low-energy photons can be used to pass the performance test for beta radiation.
   d. high-energy photons and the category for low-energy photons can be assumed to pass the test for mixtures of high-energy and low-energy photons.
   e. neutrons is appropriate for measuring neutron radiation from any source.

1.48. This standard:
   a. forms the basis for the National Voluntary Laboratory Accreditation Program for dosimetry processors.
   b. provides guidance for individual variability from reference man.
   c. provides guidance for summing the internal and external dose.
   d. is applicable to the entire range of gamma energies.
   e. is not required to be implemented by 10 CFR 20.

Scenario 14

For each of the situations below (1.49 to 1.53), select the personnel dosimeter which is most suitable for the purpose of establishing primary dose records. In