



PROGRAMMED INSTRUCTION SERIES

Radiographic Testing Volume II Safety

Written for ASNT by

Kenneth Marshall, RRPT

The American Society for Nondestructive Testing, Inc.



Documents

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Edited by: Bob Conklin, Educational Materials Editor
Assisted by: Cynthia M. Leeman, Educational Materials Supervisor

Tim Jones, Senior Manager of Publications

ASNT Mission Statement:

ASNT exists to create a safer world by promoting the profession and technologies of nondestructive testing.

About the Author

Kenneth Marshall has a bachelor's degree in health physics from Empire State College and is a registered member of the National Registry of Radiation Protection Technologists (NRRPT). He has worked as the Radiation & Laser Safety Officer for Eastman Kodak and Kodak's medical and nondestructive testing (NDT) business that became Carestream Health in 2007.

Marshall's specific experience includes implementing safety programs for employees, customers and within devices used in medical and NDT imaging. He has an extensive knowledge and working experience of radiation imaging, dosimetry and applied health physics ranging from modalities including dental X-rays through research reactors used for neutron radiography.

Contributors

The American Society for Nondestructive Testing, Inc. is grateful for the volunteer contributions, technical expertise, knowledge and dedication of the following individuals who have helped make this work possible.

Technical Reviewers

Vinodh Kumar Babu – QAF Oilfields Services Sdn. Bhd.

Vinod B. Deolalikar – NDT Management

Krutik D. Shah – Shree Vallabh NDT Services

Publication Review Committee

Terry Clausing – Drysdale & Associates, Inc.

Gary Heath – All Tech Inspection, Inc.

Glenn M. Light – Southwest Research Institute

Preface

Volume II of the *Radiographic Testing Programmed Instruction* series is devoted to the subject of radiation safety. It is meant to present some of the basic radiographic safety procedures, protective devices and detection equipment. It is not an interpretation of government regulations. For the most recent rules and regulations, contact a radiation safety officer, the U.S. Nuclear Regulatory Commission (NRC) or the appropriate Agreement State agency.

Level I and Level II candidates are encouraged to use this programmed instruction guide as a review of selected radiation safety principles outlined in Appendix A of *ANSI/ASNT CP-105: ASNT Standard Topical Outlines for Qualification of Nondestructive Testing Personnel* (2011). More specifically, topical coverage includes:

- Personnel safety and radiation protection
- Radiation survey instruments
- Radiation surveys
- Radiation survey reports
- Radiographic work practices
- Safety and health
- Biological effects of radiation
- Exposure devices
- Emergency procedures
- Storage and shipment of exposure devices and sources
- State and federal regulations

Note: A review of radiological safety principles is also outlined for both the Level I and Level II bodies of knowledge for radiographic, computed radiography, computed tomography and digital radiography testing.

It is proposed that the trainee receive 40 hours of radiation safety training prior to performing work in radiography.

Computer-Based Training

A computer-based training program is provided on the CD that accompanies this series. The material presented complements the content of all five print volumes. Navigation from the main menu allows selection of volume and chapter for review. Each chapter is broken into a number of individual lessons. Learners are not locked into a sequence but may exit a lesson at any time.

Features include:

- **Learning objectives and summaries** – bulleted points that clearly preview and sum up the material covered in each lesson.
- **Interactive “pop-up” questions** – true/false and multiple-choice questions interspersed within each lesson, with the opportunity to review slide content for questions missed. Brief explanations of incorrect responses are also provided. Learners must answer a question correctly in order to advance through a given lesson.
- **Chapter quizzes** – multiple-choice format with immediate question-by-question grading of correct/incorrect responses. A final percentage score is displayed at the end of each quiz. Answers are randomized for repeat quiz taking.
- **Volume self-tests** – 50 multiple-choice questions per test for each volume with immediate results as well as a final percentage score. Test data includes chapters and lessons missed so that learners may review specific areas for improvement. Answers are randomized for repeated use of each test.

For more information, please refer to the user instructions file included on the CD.

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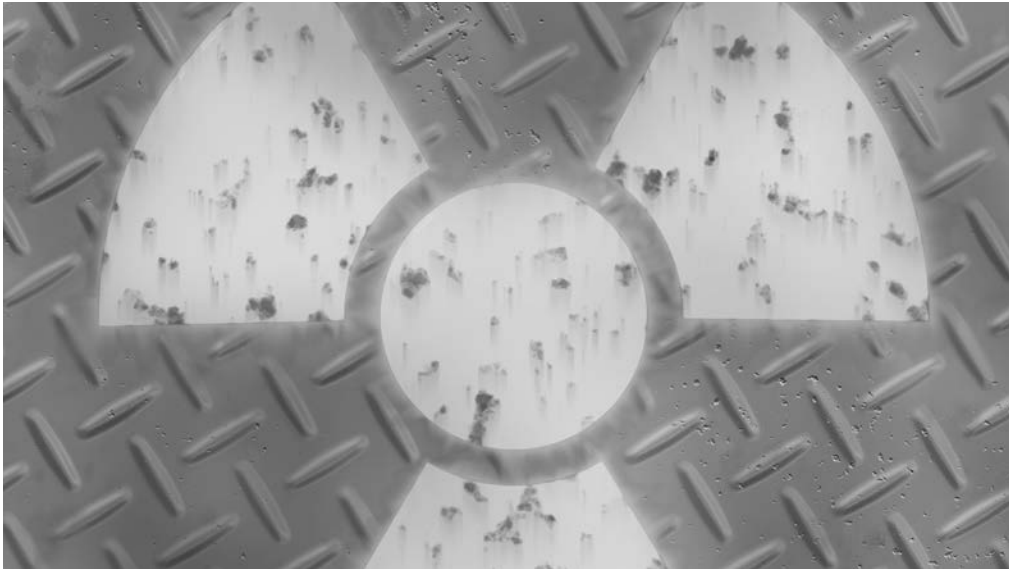
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Chapter 1

Introduction



In this chapter:

- Why some atoms are radioactive
 - Atomic and mass numbers of isotopes
- Identifying radioactive particles and emissions
 - Alpha and beta particles
- Defining the term “bremsstrahlung radiation”
- Using the decay equation to calculate activity
 - Converting curies into becquerels
- Radiological, biological and effective half-life
- Natural and manufactured sources of radiation
 - Total effective dose equivalent
 - Goal of ALARA

Radioactivity and Ionizing Radiation

Atomic Structure

Research in the late 1800s to early 1900s yielded detailed information about the structure and constituents of the atom, and led to the discoveries of X-rays and natural radioactivity. The following are milestones in the development of modern radiation physics:

- 1869** Mendeleev's periodic system of the elements.
- 1895** Röntgen discovers X-rays and creates first industrial radiograph of a shotgun barrel in the following year (1896).
- 1896** Becquerel discovers natural radioactivity in uranium.
- 1897** Thompson measures the electron.
- 1898** Marie and Pierre Curie isolate polonium and radium; coin term "radioactivity."
- 1899** Rutherford finds two types of radiation, which he names alpha and beta.
- 1900** Villard discovers gamma rays being emitted from radium.
- 1905** Einstein's special theory of relativity ($E = mc^2$).
- 1911** Rutherford discovers atomic nucleus.
- 1913** Geiger unveils prototype gas-filled radiation detector.
- 1932** Chadwick discovers the neutron.
- 1938** Nuclear fission observed.
- 1942** First nuclear chain reaction.
- 1945** First atomic bomb.

As a result of this research, we now accept that atoms comprise particles called **protons**, **neutrons** and **electrons**. (See Figure 1.1.) The center, or nucleus, of the atom contains positively charged protons and uncharged neutrons. Neutrons have slightly more mass than protons.

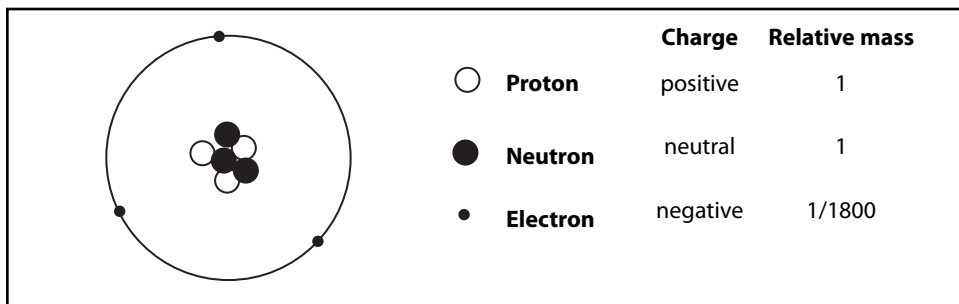


Figure 1.1: Schematic of the atom.

The nucleus is surrounded by negatively charged electrons, each of which has a mass of approximately 1/1800 that of a proton or neutron. Electrons revolve around the nucleus in a circular or elliptical orbit. Most atoms are just empty space. In fact, if all the nuclei in the entire world were packed together, the diameter of the earth would be equivalent to that of a city block — about 0.16 km (0.10 mi).

Stable versus Radioactive Atoms

Atoms that are **stable** (not radioactive) are those that do not decay. They have a proton-to-neutron ratio that is close to 1:1 for the lighter elements. This means that, for the lighter atoms, there are often equal numbers of protons and neutrons in the nucleus. As atoms get larger, the ratio approaches two protons for every three neutrons. A plot can be made of the number of protons (the Z number) versus the number of neutrons (N) for all types of atoms, as seen in Figure 1.2. This plot shows where stable atoms lie, just below the $N = Z$ line (slightly more neutrons than protons).

Most radioactive atoms lie outside this range of stability. Radioactive atoms are those that are in an unstable configuration, where there are

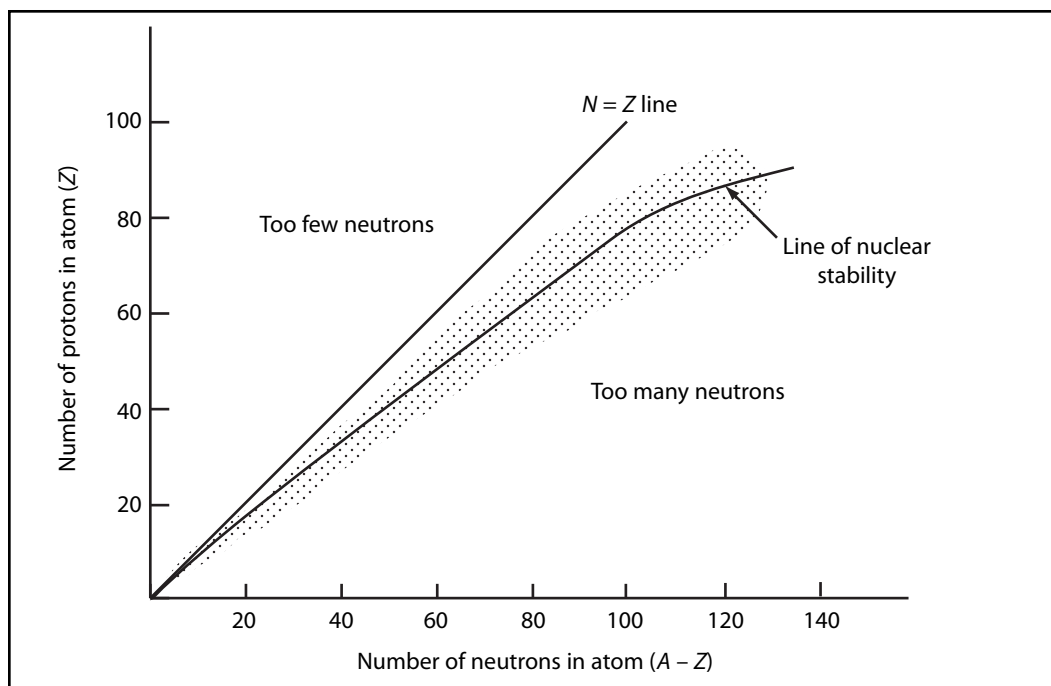


Figure 1.2: Neutron-proton plot. Dots represent stable nuclides; radionuclides are below and above the line of nuclear stability.

either too many or too few neutrons in the nucleus. All radioactive atoms seek stability, pursuing the ideal proton-to-neutron ratio of stable atoms. In the process of seeking stability, the atom releases a particle and/or a photon (ray), which is emitted with a certain energy. Depending on the atom, the emission will be in the form of **alpha**, **beta**, **gamma**, **X-** and/or **neutron** radiation. This entire process is called **radioactivity** or **radioactive decay**. Remember: **radiation is a form of energy**.

Isotopes

All atoms contain protons. The number of protons in an atom is its **atomic number**, also known as the **Z number**. Each element is defined by its atomic number; that is, all atoms of the same element contain the same number of protons within their nuclei. All hydrogen atoms contain one proton within their nuclei, all helium atoms contain two protons, and so on.

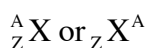
The **mass number** of an atom, also known as the **atomic mass** or **A number**, is the sum of the number of protons and the number of neutrons. For example, tritium contains one proton and two neutrons, and has a mass number of 3 — hence the name tritium. The number of neutrons (*N*) in an atom can be found by subtracting the atomic number from the mass number:

$$N \text{ (number of neutrons)} = A \text{ (mass number)} - Z \text{ (atomic number)}$$

Again taking tritium as an example, its *Z* number = 1 and its *A* number = 3; therefore, the number of neutrons is calculated as follows:

$$N = A - Z = 3 - 1 = 2$$

The *Z* number and *A* number are designated by symbols as such:



where *X* = the chemical symbol, *Z* = the number of protons and *A* = the mass number.

Atoms which contain the same number of protons but different numbers of neutrons are called **isotopes**. For example, ${}^1\text{H}$ (hydrogen), ${}^2\text{H}$ (deuterium) and ${}^3\text{H}$ (tritium), represented in Figure 1.3, are isotopes of

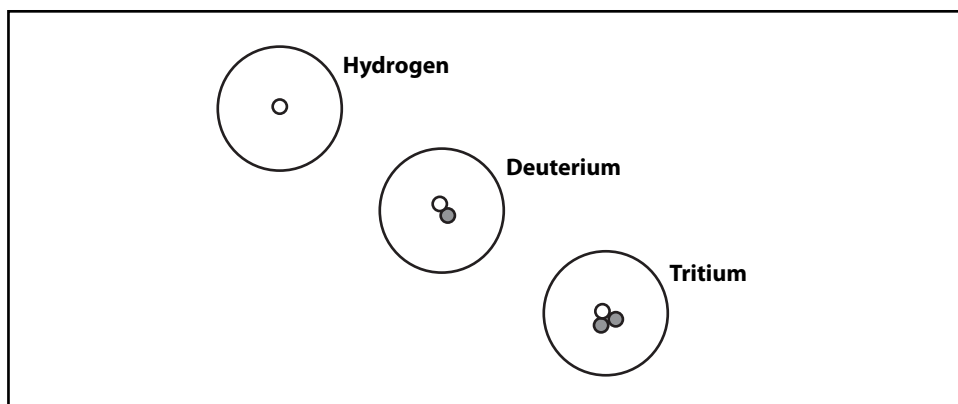


Figure 1.3: Isotopes of hydrogen.

hydrogen. Isotopes of the same element have identical chemical properties.

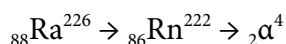
As you may recall from Volume I, isotopes can be either stable or radioactive. **Not all isotopes are radioactive.** All elements, however, have radioactive isotopes, the majority being manufactured.

The terms **radioactive isotope**, **radioisotope** and **radionuclide** can be used interchangeably.

Types of Radioactive Decay and Emissions

Alpha

Alpha (α) particles consist of two protons and two neutrons (essentially, a helium-4 atom without the electrons); the two protons and the lack of electrons cause the alpha particle to have a net charge of +2. Almost all naturally occurring alpha emitters are heavy elements with an atomic number (Z number) ≥ 83 . An example is radium-226, which decays to radon-222:



This alpha particle will have an energy of 4.78 MeV (95% of the time) or 4.60 MeV (the remaining 5% of the time). *Note:* An electronvolt (eV) is a measure of energy used when referring to radiation. The most frequently used multiples of the electronvolt are the keV (1000 eV, k = kilo) and the MeV (1 000 000 eV, M = mega).

The emission of the 4.78 MeV alpha brings the nucleus all the way to the ground state, which is the lowest energy level that can be reached by that nucleus. When the 4.60 MeV alpha is emitted, the nucleus does not reach the ground state. It reaches that state by the emission of a 0.186 MeV gamma ray, as shown in Figure 1.4. These rays are produced when there is an excess amount of energy within the nucleus and are a mechanism for ridding an excited nucleus of its excitation energy.

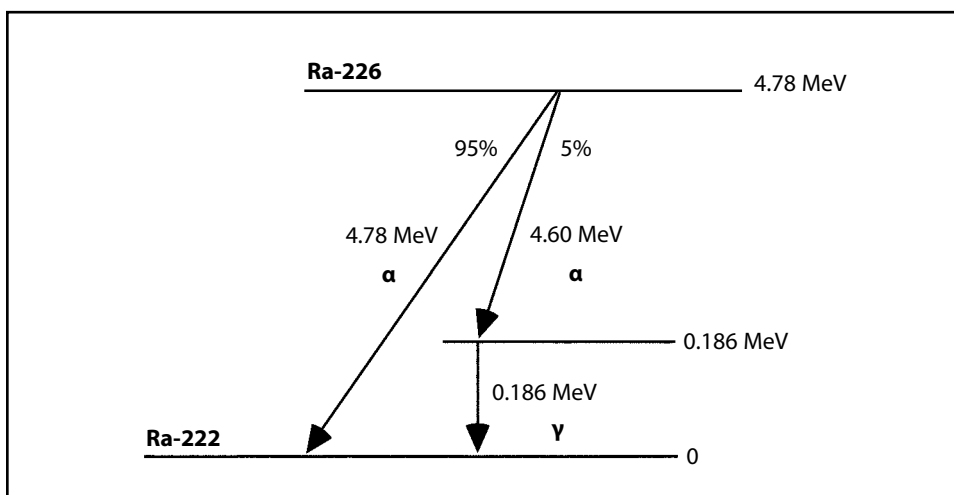


Figure 1.4: Radioactive decay.

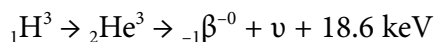
Radon-222 is also unstable and undergoes further decay, as does its subsequent daughter products, until it reaches stable lead-206. Radium-226, radon-222 and its daughter products are part of the uranium-238 series. Alpha particles are emitted with a discrete energy, generally in the megaelectronvolt range.

Because of their relatively large mass and +2 charge, alpha particles deposit a large amount of energy in a short path length. This rapid, large deposit of energy limits the penetration of the alpha particle. Most alphas can be attenuated or stopped by paper or a few centimeters of air. Alphas are not considered to present an external hazard, where they can be stopped by the dead outer layer of skin. They are most hazardous inside the body, since they deposit all of their energy within living tissue. Internally, the alpha source is in close contact with body tissue and can dissipate large amounts of energy in small volumes of tissue. The four methods of internal deposition are **inhalation, ingestion, absorption** and **injection**.

Beta

Beta decay occurs when there is an excess number of neutrons in the atom. A neutron is transformed into its constituent parts: a proton and electron. The proton remains in the nucleus and the electron (beta particle, β^-) is ejected from the nucleus with a continuous energy between zero and some maximum value.

The available energy that is not imparted to the beta is carried off by a massless particle called the **neutrino** (ν):



The mass of the daughter product (in this case, helium-3) remains the same, but the number of protons increases by one and the number of neutrons decreases by one. The 18.6 KeV is distributed between the beta and neutrino; for example, if the beta particle energy is 6 KeV, the neutrino will have an energy of 12.6 KeV. The energy spectrum for beta decay is shown in Figure 1.5.

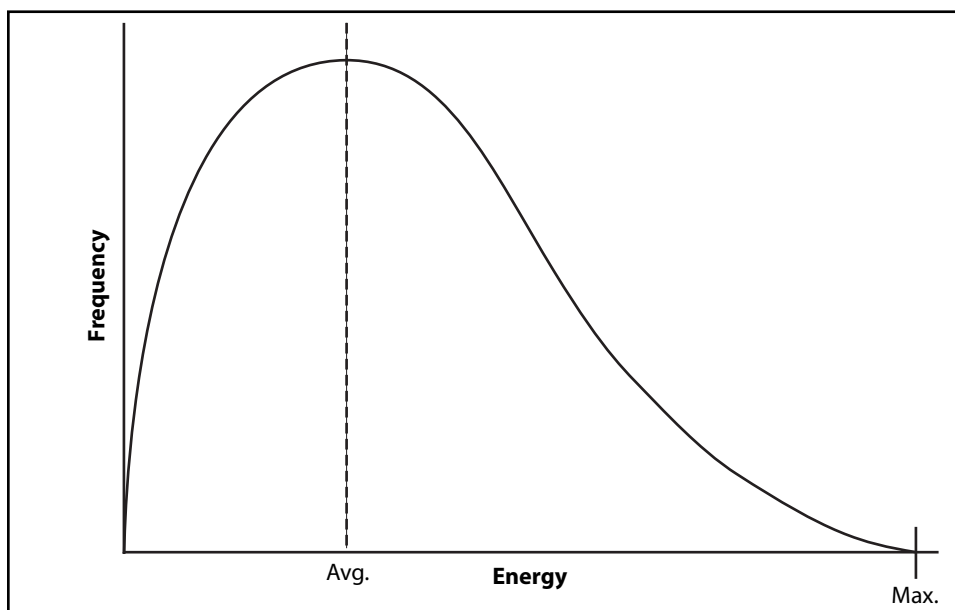


Figure 1.5: Energy spectrum of beta decay.

Because beta particles are essentially electrons, they have a charge of -1 . As far as mass is concerned, it takes more than 1800 electrons to equal the mass of one proton or neutron and more than 7200 electrons to equal the

mass of an alpha particle. Beta particles typically have greater penetrating power than alpha particles; however, because of its tiny mass, a beta particle has relatively low penetrating power compared to gamma and X-rays, making it relatively easy to shield.

Low-energy betas are considered an internal biological hazard. Tritium (^3H), with a maximum energy of 0.018 MeV, is an example of a low-energy beta emitter. However, high-energy beta particles present an external skin hazard as well. An example is strontium-90 with a maximum energy of 2.24 MeV.

Gamma Rays and X-Rays

For purposes of this discussion, gamma rays and X-rays are one and the same, except that they differ in their origin, as represented in Figure 1.6. Gamma rays originate from the nucleus of an unstable atom as a result of an excess of energy inside the nucleus. X-rays originate from the orbital electron shells surrounding the nucleus.

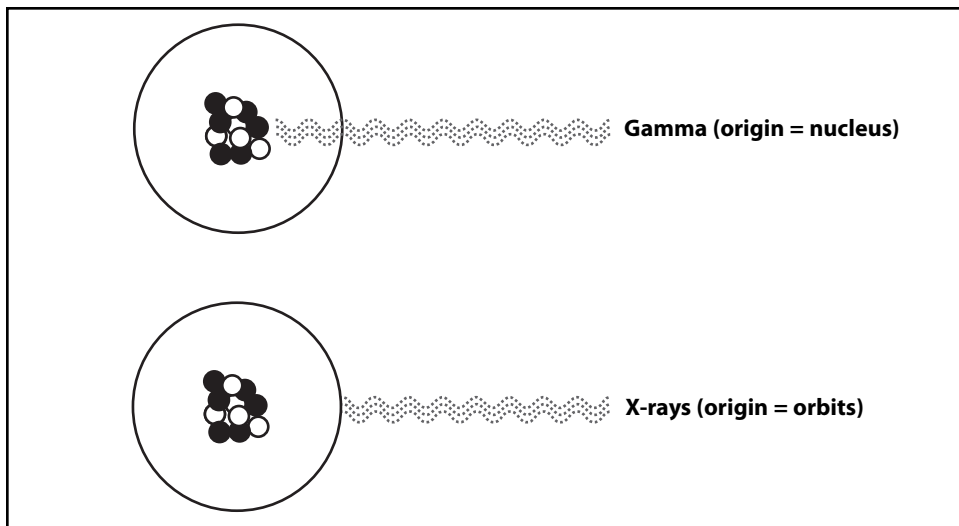


Figure 1.6: Gamma versus X-ray origin.

If an atom hasn't yet decayed to its lowest achievable energy state (ground state) by alpha, beta or positron decay or by electron capture, gamma rays will be emitted from the nucleus. These rays are produced when there is an excess amount of energy within the nucleus, providing an excited nucleus with the means to lose its excitation energy.

X- and gamma rays are **photons**, which have no mass and no electrical charge; they are forms of electromagnetic energy, like light and radio waves. Photons can be considered packets of energy rather than particles that have mass. Because photons lack mass and charge, their interactions with an absorber material are few and far between, and are dependent upon the density of the absorber. Interactions are more numerous in lead than in air, so high-density materials, like lead, make the best photon shields. Because photons expend their energy over a long range, they have great penetrating powers and are primarily external hazards. Cesium-137, cobalt-60, iridium-192 and selenium-75 are examples of gamma emitters.

Bremsstrahlung Radiation

Bremsstrahlung is a type of X-radiation that is formed when high-speed charged particles undergo rapid deceleration. (Bremsstrahlung is German for braking radiation.) When a beta particle passes close to a nucleus, a strong attractive force causes the beta particle to deviate sharply from its original path. The beta particle loses energy by emitting electromagnetic energy in the form of X-radiation. Bremsstrahlung is the process by which an X-ray tube produces X-rays. Electrons in the X-ray machine tube brake rapidly creating heat and X-radiation in the tube.

The possibility of bremsstrahlung production increases with the atomic number of the absorber. For this reason, beta shields are not made of high-Z materials such as lead, but low-Z materials like plastic or glass. To minimize the occurrence of bremsstrahlung radiation, the atomic number of the absorber should be lower than 13 (aluminum).

Neutrons

The neutron, whose mass equals 1 atomic mass unit (1/4 the size of an alpha particle), lacks any electrical charge. Because of its size and lack of charge, the neutron is fairly difficult to stop and has relatively high penetrating power. Its penetration through a medium depends upon its energy, which can range from fractions of an electronvolt to 10 MeV. Generally, the greater the neutron energy, the greater the penetration.

The best moderating material for neutrons is hydrogenous material, such as polyethylene, water or concrete. Hydrogen is effective at slowing down or moderating fast neutrons, in a manner similar to billiard balls slowing down a cue ball. (See Figure 1.7 on the next page.)

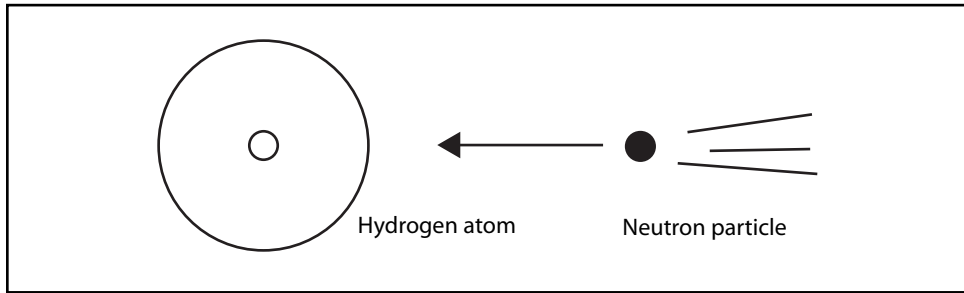


Figure 1.7: Hydrogen is a very good moderator of fast neutrons.

Neutrons are useful in specific radiographic applications where hydrogenous materials may be encased within a denser medium that would not be discernible with gamma-ray imaging. An example is the application of fuel cells, where it is desired to image hydrogen fuel within a steel housing.

Sources of neutrons for radiographic applications include sources such as californium-252, which spontaneously emits a neutron, or potential sources such as americium-beryllium (AmBe). In an AmBe source, the alphas from the americium-241 collide with the nucleus of the beryllium. Because the neutrons in beryllium are so loosely bound to its nucleus, they are ejected and can be used for neutron radiography. (A summary of the types of radiation discussed so far is presented in Table 1.1.)

Table 1.1: Summary of some characteristics of the four types of radiation discussed in this chapter.

	Alpha (α)	Beta (β)	Gamma (γ)/X-ray	Neutron
Mass	4 amu	1/1800 amu	none	1 amu
Charge	+2	-1	none	none
Penetration	low	relatively low*	great	relatively high**
Shielding	clothing	plastic	lead or concrete	polyethylene
Form	particulate	particulate	photon	particulate
Example	Rn-222	H-3	Cs-137	Cf-252, fusion
*Dependent on energy; 5.0 mm in tissue for MeV and 4 m in air per MeV.				
**Can pass through dense media, such as lead, very well, requiring hydrogenous material to shield. Fast neutrons give up 80% – 90% of their energy in elastic scattering with hydrogen in the human body.				

Radioactive Decay

The process of radioactive decay may be illustrated with reference to hydrogen atoms. The nucleus of hydrogen contains one proton and no neutrons, and has one electron in orbit around the nucleus. Deuterium (^2H) is similar to hydrogen, except that it contains one proton and one neutron. Both hydrogen and deuterium have stable nuclei. Tritium contains one proton and two neutrons, and is radioactive due to an excess number of neutrons.

Tritium seeks stability and undergoes beta decay, in which a neutron transforms itself into a proton and the nucleus emits an electron (beta particle). The result is a stable nucleus that contains two protons and one neutron, recognized as helium-3, as illustrated in Figure 1.8.

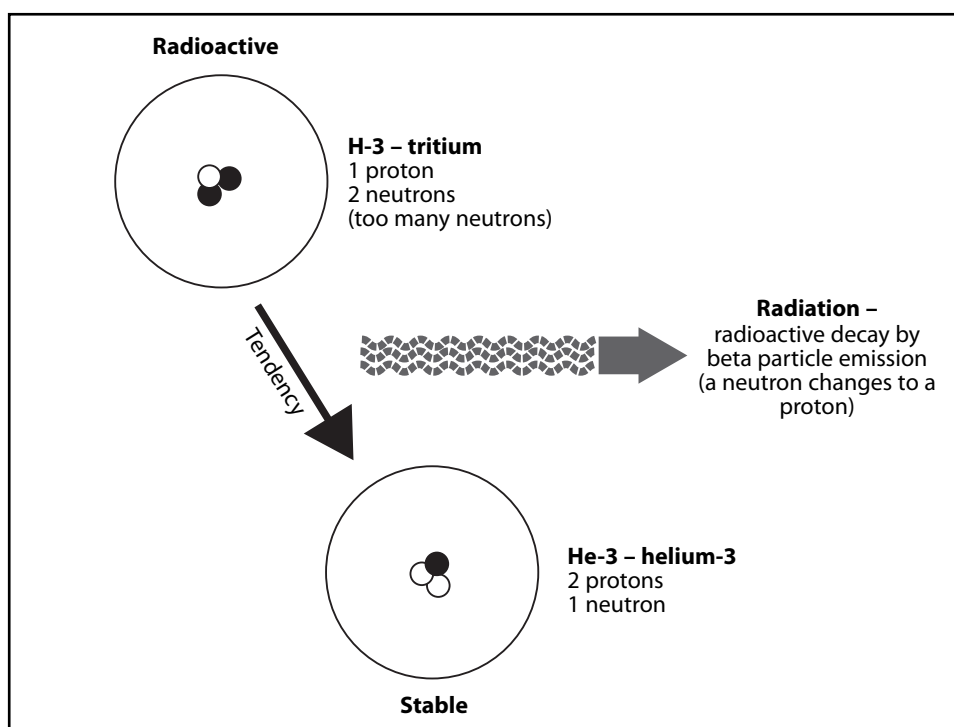


Figure 1.8: The process of radioactive decay. Unstable (radioactive) tritium decaying to stable helium-3, emitting beta radiation in the process.

A beta particle is essentially an energetic electron. Thus, a neutron comprises a proton and an electron, whose masses total that of a neutron and whose combined charges cancel each other, resulting in a net neutral charge.

Decay Equation

Radionuclides decay at different rates — some very quickly, others slowly. The **decay rate** is characteristic of a given radioisotope; it is constant and does not change. These values have been published for all radioisotopes. The **decay constant** can be used to determine the number of atoms at a certain point in time and hence the activity at that time. Lambda (λ), the decay constant, is the instantaneous fraction of atoms decaying per unit time and is used in the decay equation:

$$A = A_0 \cdot e^{-\lambda t}$$

where

- A = resultant activity after time t
- A_0 = original activity
- e = base of the system of natural logarithms (= 2.71828)
- λ = decay constant = 0.693/radiological half-life
- t = elapsed time, in the same units as the half-life

The half-life of a radioactive source is the amount of time it takes for the source be reduced to one half of its original activity. For example, phosphorus-32 has a half-life of 14.29 days. If you start with 10 mCi (0.37 GBq), what is the activity after 8 weeks?

- A = ?
- A_0 = 10 mCi
- e = 2.71828
- λ = 0.693/14.29 d
- t = 8 weeks $\times$ (7 days/week) = 56 d

Thus:

$$\begin{aligned} A &= A_0 \cdot e^{-\lambda t} \\ &= (10 \text{ mCi}) \cdot (2.71828)^{-[(0.693/14.29 \text{ d}) \cdot (56 \text{ d})]} \\ &= (10 \text{ mCi}) \cdot (2.71828)^{-[(0.0485) \cdot (56)]} \\ &= (10 \text{ mCi}) \cdot (2.71828)^{-(2.716)} \\ &= (10 \text{ mCi}) / (15.12) \\ &= 0.66 \text{ mCi (0.024 GBq)} \end{aligned}$$

Question 1.1

Let's look at a practical example for a radiographer:

An iridium-192 source, originally 100 Ci (3700 GBq), is now 365 days old. How many curies are left?

Apply the decay constant formula:

$$A = A_0 \cdot e^{-\lambda t}$$

Plug the known information into the equation and solve for A:

$$\begin{aligned} A &= ? \\ A_0 &= 100 \text{ Ci} \\ e &= 2.71828 \\ \lambda &= 0.693/73.83 \text{ d} \\ t &= 365 \text{ d} \end{aligned}$$

➡ Answer is on p. 26.

Radioactivity Units

Radioactivity or, simply stated, **activity** can be defined as the number of radioactive disintegrations occurring in a given quantity of material per unit time. The activity of radioactive material is generally expressed in terms of the **curie** or **becquerel** (where **dpm** means **disintegrations per minute**):

$$\begin{aligned} 1 \text{ curie (Ci)} &= 2.22 \times 10^{12} \text{ dpm} \\ 1 \text{ millicurie (mCi)} &= 2.22 \times 10^9 \text{ dpm} \\ 1 \text{ microcurie (}\mu\text{Ci)} &= 2.22 \times 10^6 \text{ dpm} \\ 1 \text{ nanocurie (nCi)} &= 2.22 \times 10^3 \text{ dpm} \\ 1 \text{ picocurie (pCi)} &= 2.22 \times 10^0 \text{ dpm} = 2.22 \text{ dpm} \end{aligned}$$

One curie is equal to:

$$\begin{aligned} 1 \text{ 000} &\text{ millicuries (mCi)} \\ 1 \text{ 000 000} &\text{ microcuries (}\mu\text{Ci)} \\ 1 \text{ 000 000 000} &\text{ nanocuries (nCi)} \\ 1 \text{ 000 000 000 000} &\text{ picocuries (pCi)} \end{aligned}$$

One utilization of activity is by radioisotope manufacturers, who specify the strength of the isotope by its fractions and multiples.

Question 1.2

Based on the above units, 0.66 mCi are equal to how many microcuries?

➡ Answer is on p. 26.

Many in the U.S. commonly use the traditional unit of the curie, while most other countries use the International System of Units (SI). The SI unit for activity is the **becquerel** (Bq), named for the discoverer of natural radioactivity. One becquerel is equivalent to one **disintegration per second**:

$$1 \text{ Bq} = 1 \text{ dps}$$

To convert from curies to becquerels:

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

Due to the high number of disintegrations involved in radiography — billions for a useful source — the prefix giga (10^9) is often used and the common unit is the gigabecquerel. Thus:

$$1 \text{ Ci} = 37 \times 10^9 \text{ Bq} = 37 \text{ GBq}$$

DPM versus CPM

Disintegrations per minute (dpm) is an expression of the rate of atoms actually undergoing decay. **Counts per minute** (cpm) is the unit that is measured with a radiation detection count-rate meter. The cpm is dependent upon two parameters: the efficiency and the geometry of the counting instrument.

If a source of radioactivity has a known activity of 1000 dpm and the detector shows a count rate of 100 cpm, the detector is 10% efficient for the energy of that isotope.

Net dpm can be calculated by subtracting background cpm from sample cpm and dividing the difference by the efficiency:

$$\text{Net dpm} = \frac{\text{sample cpm} - \text{background cpm}}{\text{efficiency}}$$

Half-Life

All radioisotopes undergo radiological decay, whereby an unstable atom emits radiation in the process of transformation to a different nuclide. As noted, different radioisotopes decay at different rates; each isotope has its own characteristic **decay rate**.

For example, if 1000 atoms of isotope X were present at 1 p.m. and at 3 p.m. there were only 500 X atoms left, it can be surmised that 500 (half) of the original 1000 of the atoms decayed and that it took 2 h for half of the atoms to decay. Thus, the half-life of isotope X is 2 h.

The **radiological half-life** (T_R) can be defined as the amount of time required for half of the original atoms present at a given time to decay. Depending upon the isotope, half lives range from fractions of seconds to billions of years.

If isotope X were examined after 3 p.m., the number of atoms present could be plotted over time. This would result in a graph similar to the one shown in Figure 1.9.

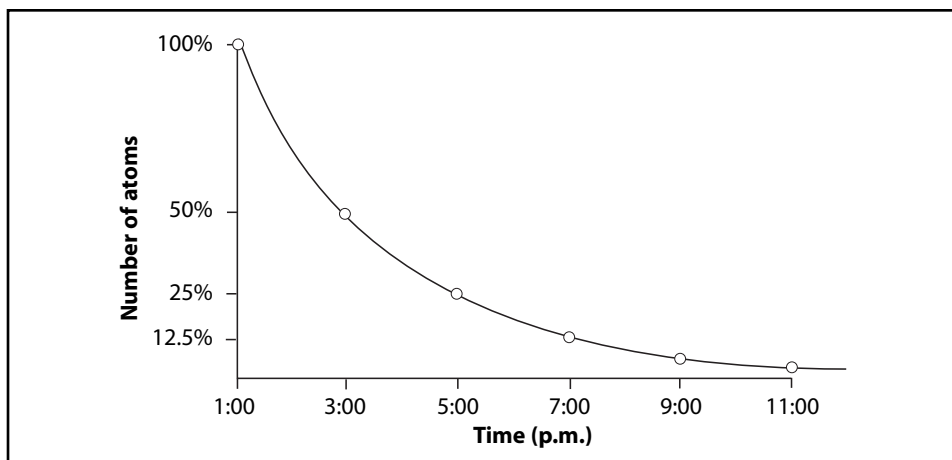


Figure 1.9: Decay graph.

Although the amount of material decreases over time, *the radiological half-life remains the same over time*. Half-life is a characteristic of a radio-isotope and is constant.

What would happen if isotope X somehow entered the body through inhalation, ingestion, injection or absorption? It would still have a half-life of 2 h (since this value does not change). However, it must be remembered that the isotope will also be eliminated from the body via excretion (urine, feces, exhalation and sweat, for example). The time required for half of the original amount of material contained inside the body to be eliminated from the body is the **biological half-life** (T_B).

A third type of half-life, the **effective half-life** (T_E), reflects the effects of the combined radiological and biological half-lives. It is the time required for the original amount of material contained inside the body to be reduced by half as a combined result of radioactive decay and biological elimination. It can be calculated by using the following equation:

$$T_E = \frac{T_B \times T_R}{T_B + T_R}$$

Using tritium as an example:

$$\begin{aligned} T_R &= 12 \text{ yr (4380 d)} \\ T_B &= 10 \text{ d} \end{aligned}$$

Plugging the values into the above formula, we have:

$$T_E = \frac{10 \text{ d} \times 4380 \text{ d}}{10 \text{ d} + 4380 \text{ d}} = 9.97 \text{ d}$$

Keep in mind that T_E and T_B are used only when the isotope enters the body.

Defining Ionizing and Nonionizing Radiation

Alpha, beta, gamma, X- and neutron radiation are forms of **ionizing radiation**. This means that they are capable of ionizing the absorber material. For example, a gamma photon may impart its energy to an electron of an electrically neutral atom, pushing that electron from its orbit. This results in a negatively charged electron and a positively charged

atom, collectively known as an **ion pair**. Thus, the gamma photon has produced ionization.

Radiation can also be in the **nonionizing** form. (The contrast between ionizing and nonionizing radiation is shown in Figure 1.10.) Visible light, lasers, microwave and radiofrequency radiation fall into the nonionizing category. Nonionizing radiation does not have enough energy to knock an electron from its orbit; therefore, it lacks the capability to form an ion pair.

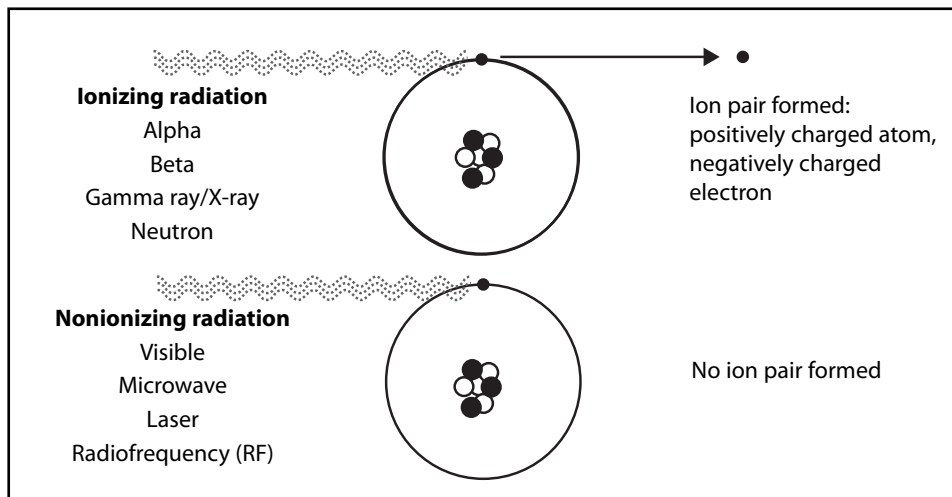


Figure 1.10: Ionization.

Personnel Exposure to Ionizing Radiation

Sources of Radiation

When discussing the biological effects from ionizing radiation, it's important to be familiar with natural and manufactured sources of radiation that we are exposed to in the nonoccupational environment.

Natural Sources

We all are exposed to radiation every day in the form of natural background radiation, which comprises approximately 82% of the average person's annual dose. A typical resident of the United States receives about 3600 μSv (360 mrem) per year — about 10 μSv (1 mrem) per day — from all sources; therefore, approximately 2950 μSv (295 mrem) per year is from natural sources.

Background radiation comprises the following:

- **Cosmic radiation** – about 8% of the dose having galactic origins. Intensity varies with latitude and elevation. Cosmic radiation consists of photons, electrons and high-energy protons.
- **Terrestrial radiation** – another 8% of the dose coming from naturally occurring radionuclides in the earth's crust, including uranium-238, thorium-232, potassium-40 and their respective decay products. These isotopes have extremely long half-lives (billions of years) and are constantly yielding decay products. (Figure 1.11 shows daughter products of the uranium and thorium series.)

Terrestrial radiation varies in different parts of the world. It is relatively high, for example, in regions of India, Brazil and Australia, due to high concentrations of various thorium- and uranium-bearing minerals (for example, monazite sands). In addition, some building materials such as concrete may contain small amounts of uranium and thorium, which can contribute to annual dose.

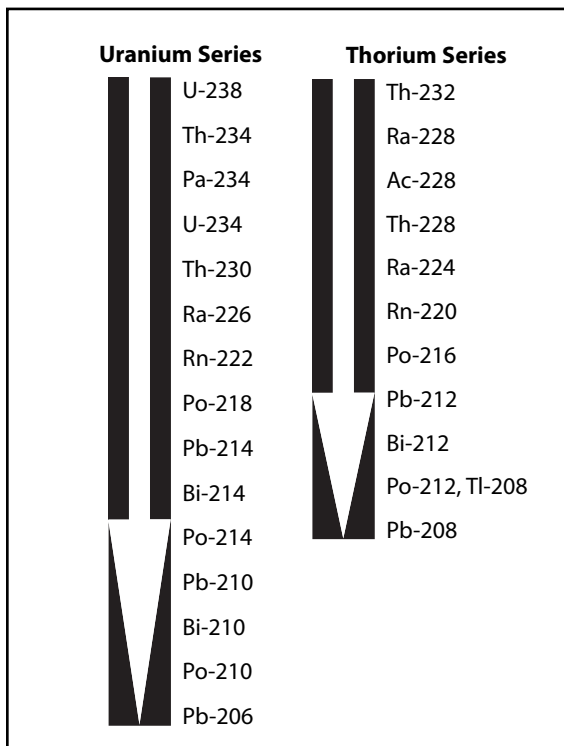


Figure 1.11: The uranium and thorium series showing major daughter (decay) products.

U-238 has a half-life of 4.5 billion years; for Th-232, the half-life is 14 billion years.

Both series emit all three types of radiation (alpha, beta and gamma) from their various constituents.

- **Internal radiation** – about 11% of a person's dose. Naturally occurring radionuclides, such as potassium-40, carbon-14 and hydrogen-3, enter the body through inhalation and ingestion. Some foods contain tiny quantities of radioactivity. Potassium-40 is the largest contributor of an internal dose.
- **Radon (and radon decay products)** – the largest contributor to the average American's dose at 55%. Radon is generated from the decay of uranium-238 in the earth's crust. It is a colorless, odorless gas that emanates from the ground and may seep into homes. Tightly insulated homes have few air exchanges over time, which tends to concentrate any radon entering the home. However, radon problems are not limited to energy-efficient homes.

Radon and daughter products do not present a significant external hazard but, when inhaled, do contribute to a person's internal dose. Radon concentrations vary widely in the U.S. per household. The Environmental Protection Agency (EPA) has estimated that 8000 to 20 000 deaths each year in the U.S. are attributable to radon-induced lung cancer, although this figure is being debated.

Manufactured Sources

Approximately 18% of the average American's radiation dose originates from manufactured sources, the majority from medical and dental diagnostic imaging, such as X-rays, nuclear medicine and computed tomography (CT) scans.

Also, radioactive materials are deliberately incorporated into a multitude of consumer products, contributing a small but measurable dose. They include gas lantern mantels (thorium), self-luminous exit signs (tritium), smoke detectors (americium), pottery glazes (uranium, thorium), compasses (promethium) and certain lenses (thorium).

A breakdown of sources of an average annual radiation dose is displayed in Figure 1.12.

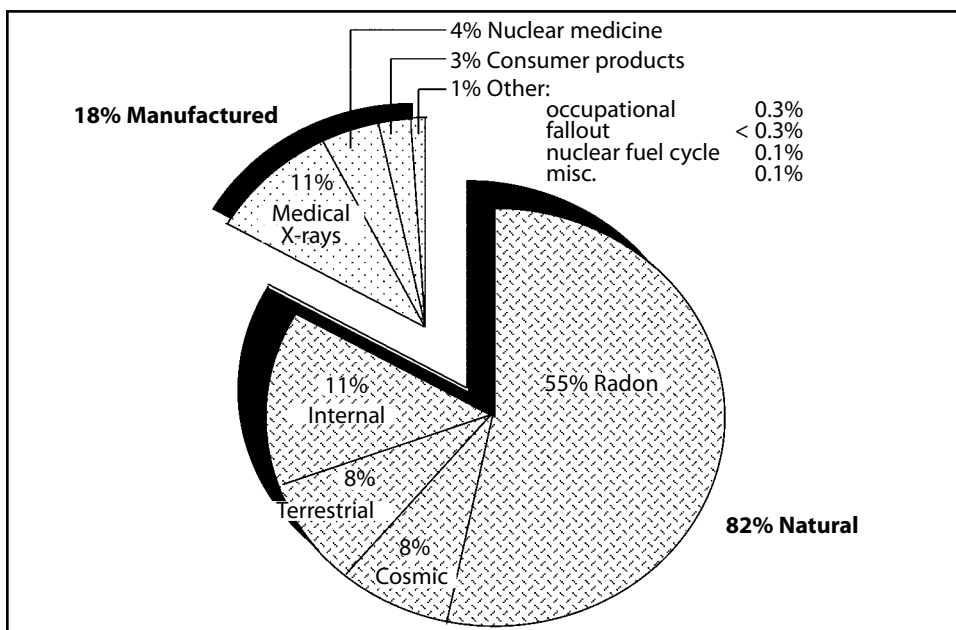


Figure 1.12: Average individual annual dose. Sources of radiation for a typical person in the U.S.

Other Sources

Other sources of radiation include the following:

- Natural gas used for cooking and heating may contain small amounts of radon.
- Persons living near a coal-fired power plant are exposed to low-levels of radium, thorium and potassium from coal combustion products.
- Phosphate fertilizers contain many members of the uranium-238 family.
- A round-trip cross-country flight results in a 10 to 20 μSv (1 to 2 mrem) dose from cosmic radiation.
- Airport X-ray machines contribute only $\sim 0.01 \mu\text{Sv}$ (0.001 mrem) per year per person.
- Smoking cigarettes can give a considerable dose to the lungs from polonium-210, a naturally occurring alpha-emitting radionuclide found in high concentrations in tobacco. The lung dose can be as high as 80 000 μSv (8000 mrem) per year for the average smoker at 1.5 packs per day.
- Nuclear power plants contribute less than 0.1% of the total dose. They must follow strict limits for doses at their site boundaries.
- Fallout from atmospheric weapons testing gives 0.3% of a dose.

Radiation Risk to Radiographers

Radiographers are specialized photographers. They have film, cameras and subjects to image. Unlike traditional photography where visible light is captured on film, a radiographer has to present the subject with a source of ionizing radiation to first penetrate the object and then capture an image of the resulting radiation on the other side of the object. Since many of the subjects are radiographed for the purposes of detecting discontinuities in dense industrial objects, the radiation required must be very intense to radiograph properly.

The levels of radiation required to image industrial objects can be significantly above levels that are considered safe for humans; in fact, they can be lethal. Since radiographers must consistently handle sources of intense radiation, radiographers are constantly challenged to keep themselves and members of the public safe from the radiographic radiation source. Ionizing radiation used in radiography cannot be detected promptly by the human senses. Unlike other dangerous chemicals, radiation has no odor and cannot be seen or felt by the human body. Because of its inability to be detected by the human senses, the radiographer is at utmost risk to inadvertently trespass into elevated radiation fields without notice.

In order to avoid exposure to this invisible hazard, radiographers must employ a series of safety controls (explained further in this book) to minimize radiation exposure. Although some safe levels of exposure to the radiographer may be acceptable, the radiographer must always be challenged to keep doses As Low As Reasonably Achievable or ALARA.

Dose Limits for Occupational Workers

Radiographers are considered trained occupational workers — that is to say, they have specific training and understanding of the hazards, risks and safety requirements for ionizing radiation at a much greater level than a member of the general public. As a radiographer, you acknowledge by the nature of your work that you are exposed to some safe limits of radiation above the public limit of 1000 μSv (100 mrem) per year.

Sources of ionizing radiation not considered part of an occupational dose include:

- Natural background radiation, including cosmic, terrestrial (including radon) and naturally occurring internal sources (for example, potassium-40).
- Diagnostic and therapeutic medical exposures (X-rays, nuclear medicine procedures and others).

Ionizing radiation included in the occupational dose limits is the sum of both internal and external exposures accrued while on the job and is referred to as the **total effective dose equivalent** (TEDE). The TEDE for occupational exposures to the whole body must not exceed 50 mSv (5 rem) per year.

The shallow dose equivalent for any extremity or for the skin must not exceed 500 mSv (50 rem) per year. The eye dose equivalent for the lens of the eye must not exceed 150 mSv (15 rem) per year.

The dose to an embryo or fetus, which results from occupational exposure of a declared pregnant woman, must not exceed 500 μ Sv (50 mrem) per month or 5 mSv (0.5 rem) over the entire course of gestation, which is approximately 39 weeks.

External radiation monitoring is required for those individuals likely to receive in excess of 10% of the occupational limits mentioned above, and for those working within or near a High or Very High Radiation Area. These values are listed in the summary Table 1.2.

Minors and Members of the General Public

The limit for minors (individuals under the age of 18) is 10% of the annual dose limits specified for adult workers. Minors are not typically authorized to work with licensed sources of ionizing radiation.

A member of the general public must not receive greater than 1000 μ Sv (100 mrem) per year from licensed or registered operations. In addition, the dose from external sources in any unrestricted area must not exceed 20 μ Sv/h (2 mrem/h). A **restricted area** is defined as any area to which access is controlled for the purpose of protecting individuals from exposure to radiation and/or radioactive material.

Table 1.2: Occupational dose limits.

Organ/Region	NRC Limit (per year)	Comments
Whole Body	50 000 μ Sv (5000 mrem)	Includes dose from both internal and external sources. The whole-body limit applies to exposure of the torso and head when the radiation is penetrating enough to irradiate tissues at a depth of 10 mm (0.39 in.) where the deeper blood-forming tissues are located.
Lens of the Eye	150 000 μ Sv (15 000 mrem)	The lens of the eye limit applies to exposure of the eye to radiation penetrating enough to irradiate the lens, at a depth of 3 mm (0.12 in.).
Extremities	500 000 μ Sv (50 000 mrem)	The extremities include the arm or leg below the elbow or knee. This limit applies to exposure of the extremities when the radiation is penetrating enough to irradiate tissues at a depth of 10 mm (0.39 in.).
Skin	500 000 μ Sv (50 000 mrem)	The skin limit applies to doses deposited in the skin when the radiation is penetrating enough to irradiate tissues at a depth of 0.07 mm (0.003 in.).
Embryo/Fetus	5000 μ Sv (500 mrem)*	Applies only when a Declaration of Pregnancy has been submitted. *Note: Stated values apply for the entire pregnancy.
Member of General Public	1000 μ Sv (100 mrem)	Applies to a member of the general public who would be near occupational settings of a radiation source.

As Low As Reasonably Achievable Dose

The goal of radiation safety is to keep all radiation exposures ALARA. This means that even if exposures are acceptable, if there is a reasonable way to reduce the exposure even further, those controls should be utilized. While there are many components to an effective radiation safety program, there are consistently three basic principles to minimize radiation exposure:

- **Time** – Minimize time duration working with radiation sources.
- **Distance** – Increase distance between the source of radiation and yourself.
- **Shielding** – Provide shielding of a suitable density to attenuate X- and gamma rays.

Chapter 1 Summary

- ☐ Stable atoms are those that do not decay; radioactive atoms seek stability, in the process releasing forms of ionizing radiation, including alpha, beta, gamma, X- and neutron radiation.
- ☐ The atomic number (Z) refers to the number of protons in an atom; the mass number (A) is the sum of the number of protons and neutrons.
- ☐ Alpha particles are not considered an external hazard; however, they are most hazardous internally, since they deposit all of their energy within living tissue.
- ☐ Low-level beta particles are considered an internal hazard; high-energy betas present an external hazard to the skin.
- ☐ Bremsstrahlung radiation occurs when high-speed charged particles undergo rapid (braking) deceleration.
- ☐ The decay constant (λ) is the instantaneous fraction of atoms decaying per unit of time.
- ☐ The activity of radioactive material may be expressed in terms of the becquerel or curie as disintegrations per minute (dpm) or disintegrations per second (dps).
- ☐ The SI unit for activity is the becquerel; 1 Bq = 1 dps.
- ☐ To convert curies to becquerels: 1 Ci = 37×10^9 Bq = 37 GBq.
- ☐ Radiological half-life (T_R) is the amount of time it takes for half of the original atoms present at a given time to decay.
- ☐ Biological half-life (T_B) is the time required for half of the original amount of material in the body to be eliminated.
- ☐ Effective half-life (T_E) is the time required for the original amount of material inside the body to be reduced by half as a result of both radiographic decay and biological elimination.
- ☐ Sources of radiation exposure comprise both natural and manufactured sources.
- ☐ Total effective dose equivalent is the sum of both internal and external exposures accrued in an occupational setting.
- ☐ As Low as Reasonably Achievable (ALARA) is the goal of reducing radiation exposure through time, distance and shielding.

Answers to Chapter 1 Questions

Question 1.1

Answer: **3.25 Ci (120.25 GBq).**

This answer is obtained by applying the decay constant formula:

$$A = A_0 \cdot e^{-\lambda t}$$

The values needed to solve the equation are as follows:

$$\begin{aligned} A &= ? \\ A_0 &= 100 \text{ Ci} \\ e &= 2.71828 \\ \lambda &= 0.693/73.83 \text{ d} \\ t &= 365 \text{ d} \end{aligned}$$

Plugging in the appropriate values, we get:

$$\begin{aligned} A &= A_0 \cdot e^{-\lambda t} \\ &= (100 \text{ Ci}) \cdot (2.71828)^{-[(0.693/73.83 \text{ d}) \cdot (365 \text{ d})]} \\ &= (100 \text{ Ci}) \cdot (2.71828)^{-[(0.009386) \cdot (365)]} \\ &= (100 \text{ Ci}) \cdot (2.71828)^{-(3.426)} \\ &= (100 \text{ Ci}) / (30.75) \\ &= 3.25 \text{ Ci (120.25 GBq)} \end{aligned}$$

Question 1.2

Answer: **660 μ Ci.**

If millicuries are factored as 10^{-3} and microcuries as 10^{-6} , to convert from mCi to μ Ci, move the decimal place three places to the right. Thus: 0.66 mCi is equivalent to 660 μ Ci. In Si units, this is equivalent to 0.024 GBq, as follows:

$$660 \mu\text{Ci} = 0.00066 \text{ Ci} \times 37 = 0.024 \text{ GBq}$$

Chapter 1 Review

1. Lead has an atomic number of 82. How many protons does lead have?
2. Define what is meant by an isotope of a stable atom. Are all isotopes radioactive?
3. True or false: Gamma rays originate from the electron cloud of an atom.
4. The average U.S. citizen receives approximately how much radiation from natural and manufactured sources?
5. Which of the following best describes the term photon?
 - A. A charged particle emitted from the nucleus of an atom.
 - B. A packet of energy that has no mass and no charge.
 - C. A charged particle emitted from the electron cloud of an atom.
6. The embryonic dose limit for a declared pregnant female employee is:
 - A. 500 μ Sv (50 mrem).
 - B. 1000 μ Sv (100 mrem).
 - C. 5000 μ Sv (500 mrem).
7. True or false: The greatest contributor of radiation dose to the average person in the U.S. is medical X-rays.

8. Radiological half-life is defined as:
 - A. The amount of time required for half of the original atoms present at a given time to decay.
 - B. The amount of energy required to kill 50% of the population over 60 days.
 - C. The amount of time required for half of the amount of ingested radioactive material to be excreted or removed by the body.
9. The German word for braking radiation and the principal cause of X-ray production in common X-ray tubes is:
 - A. Bremsstrahlung.
 - B. Roentgen.
10. True or false: The best shield for neutrons is lead.

Chapter 1 Review Key

1. **82.**

The atomic number represents the number of protons in a nucleus. The number of protons is also referred to as the Z number.

2. **An isotope is an atom that contains the same number of protons but different numbers of neutrons.**

Not all isotopes are radioactive. For example, deuterium, an isotope of stable hydrogen, is not radioactive.

3. **False** – Gamma rays originate from the nucleus of an atom, usually as the result of nuclear instability. X-rays are generated from the electron cloud. Other than their origins, X-rays and gamma rays are both photons and behave similarly when interacting with matter.

4. Approximately 3600 μSv (360 mrem) — or another way to remember this is about 10 μSv (1 mrem) per day.

The average U.S. citizen receives approximately 3000 μSv (300 mrem) per year from natural sources of radiation, the largest contributor being radon and its progeny contributing approximately 2000 μSv (200 mrem) per year. The remaining 600 μSv (60 mrem) per year is from manufactured sources, largely from medical X-rays, nuclear medicine and other procedures.

5. **B** – A “packet of energy” that has no mass and no charge.

A photon is neither a particle (it has no mass) nor does it have a charge (it is neutral). A photon is a mechanism in which energy is transferred from one place to another when no mass and no charge are involved, such as visible light or radio waves. It is often explained that it is not an object like a particle but rather a “packet of energy.”

6. **C** – 5000 μSv (500 mrem) for the gestation period of the pregnancy.
7. **False** – The largest contributor is radon and its progeny, a naturally occurring radioactive isotope.
8. **A** – Radiological half-life can be defined as the amount of time required for half of the original atoms present at a given time to decay.
9. **A** – Bremsstrahlung.
10. **False** – Neutrons tend to shield best with atoms close to their own size. A proton or hydrogen atom is best. Lead is less effective than hydrogen-rich materials.

Chapter 2

Control of Hazards from External Radiation Sources



In this chapter:

- Importance of time, distance and shielding
- Using the inverse square law to calculate intensity
 - Density of shielding materials
- Determining shield thickness using half-value and tenth-value layers
 - Narrow versus broad beam radiation
 - Primary versus secondary radiation beam
- Use of the linear attenuation coefficient in shielding applications
 - Computing the “buildup factor” with regard to shielding

Time, Distance and Shielding

The three basic safety and control concepts used in radiation protection are time, distance and shielding.

Time

As would be expected, the less time spent near or with a radioactive source, the lower the exposure. It is sometimes necessary in work situations to spend time near materials that are radioactive. Exposure rates from common isotopes currently in use are generally not high, but are measurable. It is prudent to spend no more time than is required working with or near radioactive materials.

Distance

It also may be intuitive that the greater the distance between you and the radioactive source (or area), the lower the exposure. Radiation from a point source follows the **inverse square law**, which states that intensity falls off with the square of the distance. (See Figure 2.1.)

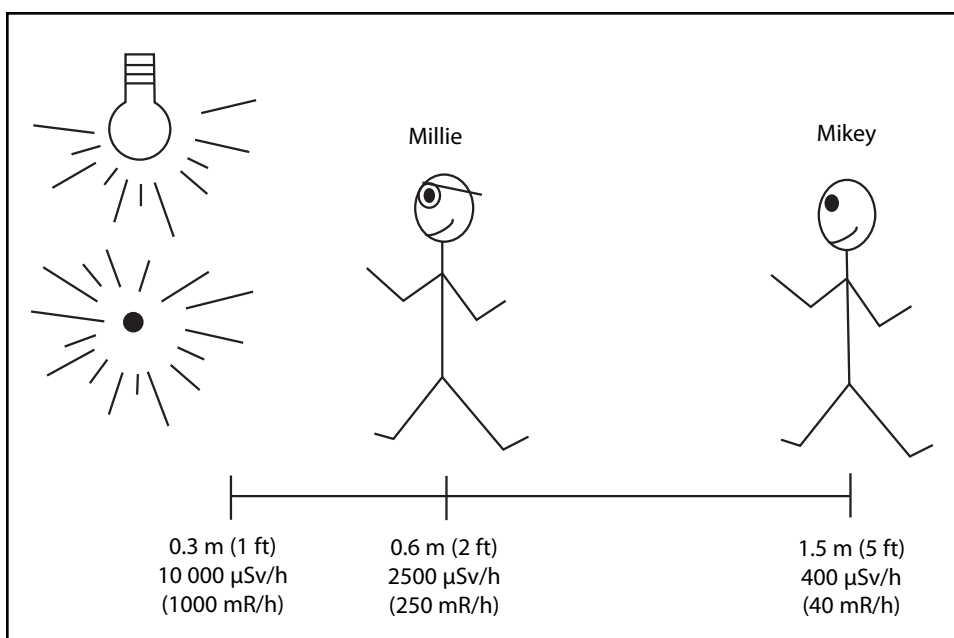


Figure 2.1: The inverse square law for a point source can pertain to a radioactive source as well as a light bulb. By being 0.9 m (3 ft) farther away from the source than Millie, Mikey receives less than 1/6 the exposure. He also receives less than 1/6 the light from the light bulb that Millie receives.

The intensity of a source at a given distance can be estimated by using this law:

$$I_1 \times (D_1)^2 = I_2 \times (D_2)^2$$

where

I_1 = intensity at point 1

I_2 = intensity at point 2

D_1 = distance 1

D_2 = distance 2

For example, if a point source has a known exposure rate of 10 000 $\mu\text{Sv/h}$ (1000 mR/h) at 0.3 m (1 ft), the exposure rate can be calculated for a distance of 1.5 m (5 ft) from the source. Here is the calculation using SI units:

$$10\,000\ \mu\text{Sv/h} \times (0.3\ \text{m})^2 = I_2 \times (1.5\ \text{m})^2$$

$$\frac{10\,000\ \mu\text{Sv/h} \times (0.3\ \text{m})^2}{(1.5\ \text{m})^2} = I_2$$

$$\frac{10\,000\ \mu\text{Sv/h} \times 0.09\ \text{m}^2}{2.25\ \text{m}^2} = I_2$$

$$\frac{900\ \mu\text{Sv/h}}{2.25} = I_2$$

$$400\ \mu\text{Sv/h} = I_2$$

This is how the calculation unfolds using traditional units:

$$1000\ \text{mR/h} \times (1\ \text{ft})^2 = I_2 \times (5\ \text{ft})^2$$

$$\frac{1000\ \text{mR/h} \times (1\ \text{ft})^2}{(5\ \text{ft})^2} = I_2$$

$$\frac{1000\ \text{mR/h}}{25} = I_2$$

$$40\ \text{mR/h} = I_2$$

Thus, a 10 000 μSv (1000 mR/h) point source at 0.3 m (1 ft) would yield about a 400 $\mu\text{Sv/h}$ (40 mR/h) intensity at 1.5 m (5 ft), a factor of 25 times less.

Question 2.1

Let's apply what we have learned:

If a radiography point source has a known exposure rate of 33 000 $\mu\text{Sv/h}$ (3300 mR/h) at 0.3048 m (1 ft), what exposure rate can be calculated for a distance of 9.144 m (30 ft) from the source?

➡ Answer is on p. 47.

Shielding

The exposure from a radioactive source can be decreased by placing appropriate shielding between the source and you. Shielding serves to attenuate radiation so that the radiation deposits its energy in the shielding material instead of in your body. The effectiveness of any shielding depends on three parameters:

1. The type of shielding material.
2. The thickness of the material.
3. The type of radiation to be shielded.

Shielding for Alpha, Beta, Gamma and X-Rays

For example, 99.1 mm (3.9 in.) of air will attenuate almost any alpha particle but would stop very few gamma photons.

Shielding materials include:

gamma/X-rays lead, concrete
alpha clothing, air
beta plastic, aluminum (low-Z materials)
neutron water, polyethylene, concrete

The thickness required for a shield to be effective depends upon the energy and, in the case of radioactive material, the activity of the radiation source. The most common shielding materials for gamma and X-radiation are as follows, in order of most dense (1) to least dense (5):

1. **Depleted uranium (DU)** – uranium depleted of its fissionable assets. Typically used in radiographic cameras as a shield/housing for a radioactive source.

2. **Tungsten** – typically utilized for radiographic collimators.
3. **Lead** – used in shielding, storage containers (pigs) and some collimators.
4. **Iron/steel** – common iron-bearing metal alloys used as a shielding material.
5. **Concrete** – common shielding material found in everyday construction so that it can be often utilized as an additional safety barrier for a radiographer. Since concrete is such a common construction material, found in buildings and industrial settings, a radiographer may be able to take advantage of its shielding characteristics, despite its being less dense than other materials.

As a rule, the more dense a material, the greater the efficiency at shielding gamma and X-ray exposure. In addition, when dealing with gamma and X-radiation, the greater the energy of the photon, the greater the thickness of shielding required. Although it takes less lead than concrete to attenuate the same level of radiation, it may not be economically viable to construct a radiographic room of lead since concrete is less expensive despite needing a greater volume.

Note: Each facility must create its own shielding plan in accordance with licensing and with the aid of a health physicist. Prescriptions for shielding construction plans can be found in separate handbooks such as those issued by the National Council on Radiation Protection and Measurements (NCRP).

Half-Value Layer

The thickness of a shield that will decrease the original intensity by one-half is called the **half-value layer** (HVL). Actual HVLs are dependent upon photon energy and shielding material density. A commonly used rule of thumb is that the HVL for lead is 12.7 mm (0.5 in.) per 1 MeV of photon energy. The equation to use for a half-value layer application is:

$$D = D_o (1/2)^n$$

where

D = the shielded exposure rate

D_o = the unshielded exposure rate

n = the number of shielding material half-thicknesses

HVLs are used for only X- and gamma-ray emitters. For example, it has been observed that a 7.9 mm (0.3 in.) thickness of lead will attenuate about half of the gamma photons being emitted from cesium-137. Therefore, the HVL of Pb is 7.9 mm (0.3 in.) for cesium-137. Two HVLs would attenuate the original intensity by $1/2 \times 1/2 = 1/4$; three HVLs by $1/2 \times 1/2 \times 1/2 = 1/8$; and so on. (See Figure 2.2.)

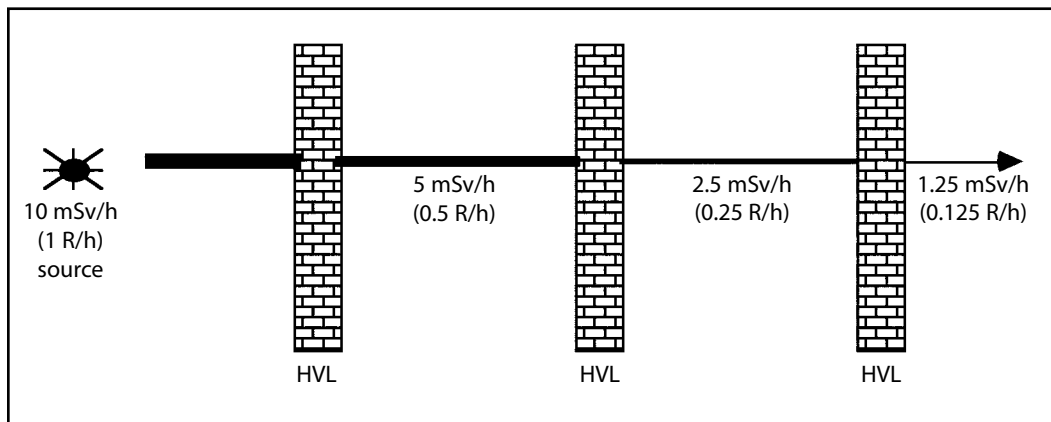


Figure 2.2: Three half-value layers decrease intensity by 1/8.

Tenth-Value Layer

A **tenth-value layer** (TVL) is the thickness of shielding material required to reduce primary beam photon intensity to one-tenth of its original value. (See Figure 2.3.) The equation for the tenth-value layer is:

$$D = D_0 (1/10)^n$$

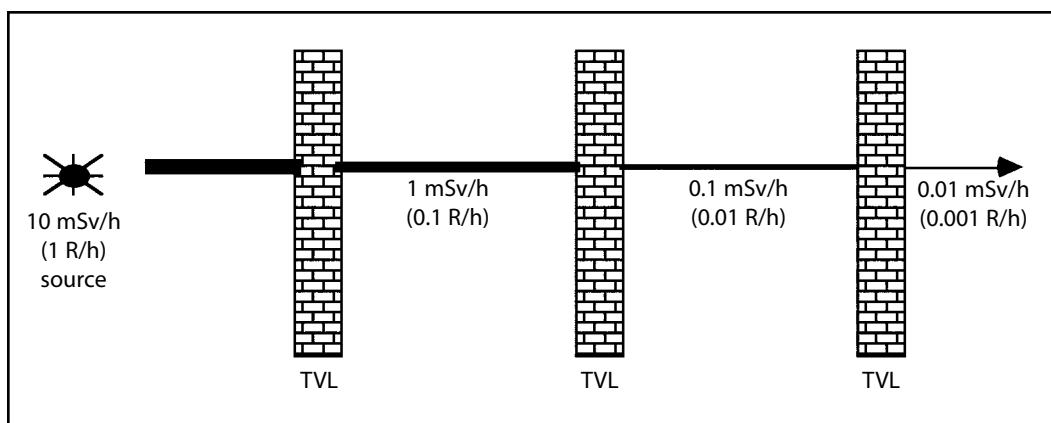


Figure 2.3: Three tenth-value layers decrease intensity by 1/1000.

where

D = the shielded exposure rate

D_o = the unshielded exposure rate

n = the number of shielding material tenth-thicknesses

HVL and TVL values can be obtained from reference texts such as NCRP Report No. 147 (*Structural Shielding Design and Evaluation for Medical X-Ray Imaging Facilities*), Appendix D. Commonly encountered TVLs and HVLs are displayed in Table 2.1. (Note: 1 TVL = 3.323 HVLs.)

Table 2.1: Half-value layer (HVL) and tenth-value layer (TVL) values for two sources.

Material	HVL and TVL Values			
	Co-60		Ir-192	
	HVL	TVL	HVL	TVL
Depleted Uranium	6.5 mm (0.26 in.)	22 mm (0.87 in.)	2 mm (0.08 in.)	6.5 mm (0.26 in.)
Lead	12.4 mm (0.49 in.)	41 mm (1.61 in.)	5.1 mm (0.20 in.)	16 mm (0.63 in.)
Tungsten (Collimator)	7.9 mm (0.3 in.)	26.7 mm (1.05 in.)	3.4 mm (0.13 in.)	11.2 mm (0.44 in.)
Steel	22.1 mm (0.87 in.)	73.7 mm (2.9 in.)	15.5 mm (0.61 in.)	50.8 mm (2.0 in.)
Concrete	60.5 mm (2.4 in.)	205 mm (8.1 in.)	44.5 mm (1.75 in.)	150.5 mm (5.9 in.)

Question 2.2

Let's apply what we have discussed:

Using the half-value layer formula of $D = D_o(1/2)^n$, calculate the thickness of lead in millimeters required to reduce a 300 mSv/h (30 R/h) cobalt-60 field to a radiation area of 50 μ Sv/h (5 mR/h). The HVL is given as cobalt-60 = 12.4 mm of lead.

Once again, our formula is given as:

$$D = D_o(1/2)^n$$

where

D = the shielded exposure rate

D_o = the unshielded exposure rate

n = the number of shielding material half-thicknesses

First, let's convert millisieverts (roentgens) to microsieverts (milliroentgens), as follows:

$$300 \text{ mSv/h (30 R/h)} \times 1000 = 300\,000 \text{ } \mu\text{Sv/h (30\,000 mR/h)}$$

Now what we know is:

$D = 50 \text{ } \mu\text{Sv/h (5 mR/h)}$

$D_o = 300\,000 \text{ } \mu\text{Sv/h (30\,000 mR/h)}$

n = the number of shielding material half-thicknesses. (Note:

Another way of expressing n is $n = \text{thickness} \div \text{HVL}$.)

HVL = 12.4 mm

What we want to solve for is thickness, which is a component of n in the above formula. We can rearrange the formula $D = D_o(1/2)^n$ to solve for thickness as follows. First, we must isolate n by dividing both sides of the equation by D_o as shown:

$$\frac{D}{D_o} = \frac{D_o(1/2)^n}{D_o}$$

Since the two instances of D_o cancel each other out on the right-hand side of the equation, we are left with:

$$\frac{D}{D_o} = (1/2)^n$$

Next, divide each side by $1/2$ to get n by itself:

$$\frac{\frac{D}{D_o}}{1/2} = \frac{(1/2)^n}{1/2}$$