Outcome Competencies

After completing this chapter, the user should be able to:
1. Define underlined terms used in this chapter.
2. Describe the physics of radiation interaction with matter.
3. List categories of ionizing radiation.
4. Explain dosimetry and attenuation.
5. List radiation detection devices.
6. Recall the operating principles for radiation detection devices.
7. Summarize the sources of exposure to ionizing radiation.
8. Describe radiation production equipment.
9. Describe the biological consequences of exposure to ionizing radiation.
10. Recall agencies that regulate ionizing radiation.

Prerequisite Knowledge

Basic college physics, college chemistry, mathematics to the level of calculus.

Prior to beginning this chapter, the user should review the following chapters:

<table>
<thead>
<tr>
<th>Chapter Number</th>
<th>Chapter Number</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>Environmental and Occupational Toxicology</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>Occupational Exposure Limits</td>
</tr>
</tbody>
</table>

Key Terms

absorption • agreement state • atomic • atomic mass • atomic mass unit • atomic number • atomic weight • attenuation • beta • bremsstrahlung • Compton effect • contamination • critical target • densitometer • gamma rays • Geiger counter • hot lab • ionization chamber • ionizing chamber • ionizing radiation • isomers • isotope • LD_{37} • LD_{50} • metastable • Naturally Occurring Radioactive Material (NORM) • neutrino • neutron • nucleon • nuclear force • nuclear regulatory commission • nuclides • pair production • photoelectric effect • positrons • proportional counter • radioactivity • radionuclide • radon progeny • sensitive volume • sensitometer • specific activity • standard man • survey • thermoluminescent dosimetry • tissue equivalent • TLD chips • total absorption process

Key Topics

I. Radiation
A. Ionizing Radiation-Photons and Particles

II. Physical Aspects of Production of Ionizing Radiation
A. Electromagnetic Radiation (X-Rays, Gamma Rays, Bremsstrahlungen, Cosmic Electromagnetic Rays)
B. Gamma Decay
C. Isobasic Transitions
D. Alpha Decay

III. Dosimetry
A. Attenuation Processes
B. Attenuation of Photons
C. Attenuation of Particles

IV. Radiation Measurements
A. External Monitoring
B. Instrument Use Considerations
C. Internal Monitoring

V. Sources of Exposure from Ionizing Radiation
A. Natural Background Radiation
B. Radon
C. Artificial and Technologically Enhanced Radiation Exposure
D. Consumer Products
E. Industrial Uses
F. Nuclear Reactors
G. X-ray machines

VII. Biological Consequences of Ionizing Radiation
A. Dose Response Curve
B. Linear No threshold Theory

VIII. Applicable Regulations
A. Agencies
B. Dose Limits
C. ALARA

IX. Radiation Protection
A. External Exposure Controls
B. Contamination Controls

X. Summary
Radiation

Ionizing Radiation-Photons and Particles

Ionizing radiation is a general term applied to both electromagnetic waves and/or particulate radiation capable of producing ions by interaction with matter. Ionization is the process of removing electrons from neutral atoms, which results in the breaking up of an electrically neutral atom or molecule into charged components. If enough energy is supplied to remove electrons from the atom, the remaining atom has a positive (+) charge. The positively charged atom and the negatively charged electron are called an ion pair. Do not confuse ionization with radiation. Radiation is simply energy and/or mass in motion. As a result of this energy, ionization may occur. Ions (or ion pairs) produced as a result of radiation interactions with atoms allow the detection and measurement of radiation.

Ionizing radiation is energy (particles or rays) emitted from radioactive atoms (excluding atoms used during X-ray production, i.e., artificially produced) that can cause ionization in the atoms with which it interacts. The four basic types of ionizing radiation that are of primary concern in the nuclear industry are alpha particles, beta particles, gamma or X-rays, and neutrons.\(^1\)

Nonionizing radiation does not have a sufficient amount of energy to ionize an atom with which it interacts. Examples of nonionizing radiation include radar waves, microwaves, and visible light. Although the word radiation can be used to mean ionizing or nonionizing radiation, it is most often used to mean ionizing radiation.

Only certain combinations of neutrons and protons result in stable atoms. If there are too many or too few neutrons for a given number of protons, the resulting nucleus contains too much energy and is not stable. The unstable atom attempts to become stable by giving off excess energy in the form of particles and/or waves (radiation). These unstable atoms are also known as radioactive atoms. The electromagnetic wave from a nucleus is called a gamma.

Radioactivity is the property of the nucleus of atoms that contains an unstable configuration of protons or neutrons. Radioactive atoms emit radiation in the form of particles or energy. A radioactive material is any material containing unstable radioactive atoms that emit radiation.

Radioactive contamination is radioactive material in an unwanted place. (There are certain places and situations where radioactive material is beneficial.) It is important to note that exposure to radiation does not result in contamination of the worker. Radiation is a type of energy and contamination is a material.

Radiation dose units are limited to ionizing radiation photons and ionizing particles (Tables 23.1, 23.2, and 23.3). Typically, ionizing radiation photons are defined in terms of energy expressed in multiples of the electron volt, keV (thousand electron volts) or MeV (million electron volts), rather than wavelength (\(\lambda\)) or frequency (Hz). Wavelength units typically apply to the part of the electromagnetic spectrum in the optical range.

<table>
<thead>
<tr>
<th>Table 23.1 — Radiation Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose Unit</td>
</tr>
<tr>
<td>Exposure dose</td>
</tr>
<tr>
<td>Activity</td>
</tr>
<tr>
<td>Absorbed dose</td>
</tr>
<tr>
<td>Dose equivalent</td>
</tr>
<tr>
<td>Linear energy transfer</td>
</tr>
<tr>
<td>Absorbed dose</td>
</tr>
</tbody>
</table>

KERMA = kinetic energy released in material
infrared, and microwave region and frequency units to the lower energy portion of radio and television regions. Though physically the same in any unit, measurement in the electromagnetic spectrum historically is described in the unit in which the component can be measured. For biological measurement that compares ionizing photons with ionizing particles, measurement in energy units is required. It is appropriate to state units of ionizing photons in keV or MeV. Within this chapter the term “radiation” assumes ionizing radiation. All the radiation rays used in health physics are listed in Table 23.4. The common symbols for particles are noted in Table 23.5.

Nomenclature pertaining to electromagnetic waves refers to their origin. Photons produced from nuclear transition emission are called gamma rays, typically MeV. Those photons produced from electron transitions in high atomic mass nuclides are called characteristic X-rays. Photons produced from free electron interactions, typically keV, are called X-rays or bremsstrahlungen. A bremsstrahlung (plural bremsstrahlungen) is an X-ray created when a high energy particle is negatively accelerated over a very short distance and the kinetic energy is transformed into an ionizing photon. Depending on the rate of deceleration, the energy of the photon ranges between the lower limit of ionizing radiation and the maximum kinetic energy of the particle. The particle can be any charged particle such as a beta from radioactive decay, a proton in a cyclotron, or electrons in an X-ray machine. Unwanted bremsstrahlung radiation is of concern for protection against radioactivity.

Photons that are extraterrestrial in origin are called cosmic electromagnetic rays. There are also cosmic particles. Characteristic X-rays, bremsstrahlungen, X-rays in general, gamma rays, and cosmic electromagnetic rays are collectively called photons, independent of origin and of energy. Direct reference made to the energy (wavelength, frequency) of the photon or groups of photons is termed quality, whereas the reference to the number of photons may be termed quantity. Graphical displays of quantity versus quality are two-dimensional spectra.

Physics units are limited to ionizing radiation with specific applications. Radiation quality or quantity does not necessarily imply a predictable radiation dose response. There are dose equivalent units for that conversion. See Table 23.6 for the application of radiation and Table 23.3 for the definition of the units. The scaling factors in Table 23.6 are used to convert a dose unit to a radiobiological response unit. These factors are energy-dependent, and correct usage involves table conversions at a specific energy.

### Table 23.2 — Scaling Factors for Ionizing Radiation

<table>
<thead>
<tr>
<th>Relative biological effectiveness (RBE)</th>
<th>ratio of a standard cell effect to test effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality factor (QF)</td>
<td>factor to convert Gy to Sv (rad to rem)</td>
</tr>
<tr>
<td>f-factor</td>
<td>factor to convert R to Gy (energy dependent)</td>
</tr>
</tbody>
</table>

### Table 23.3 — SI Units Used in Radiation Protection

**Exposure**
- Roentgen R, the charge produced in air by X-rays or gamma rays. The SI unit is in terms of coulombs per kilogram of air (C/kg).
  - 1 R = 2.58 × 10^{-4} C/kg
  - 1 C/kg = 3876 R
- KERMA (kinetic energy released in material)
  - The SI unit is the gray.
  - 1 gray (Gy) = 100 rad
  - 1 rad = 0.01 Gy
- An exposure of 1 R (2.58 × 10^{-4} C/kg) corresponds to an air KERMA of about 0.87 rad (8.7 mGy) or a tissue KERMA of about 0.97 rad (9.7 mGy).

**Radiation Absorbed Dose**
- The SI unit is the gray (Gy).
  - 1 gray = 100 rad
  - 1 rad = 0.01 Gy

**Radiation Dose Equivalent**
- The SI unit is the sievert (Sv).
  - 1 sievert (Sv) = 100 rem
  - 1 rem = 0.01 Sv

**Activity**
- The SI unit of activity is the becquerel (Bq).
  - 1 becquerel (Bq) = 1 disintegration per second
  - 1 Bq = 2.7 × 10^{-11} Curie (Ci)
  - 1 Ci = 3.7 × 10^{10} Bq = 37 Gbq

**Additional Useful Conversions**
- 1 µCi = 37 kBq
- 1 mCi = 37 MBq
- 1 Bq = 27 pCi
- 370 MBq = 10 mCi
- 1 µSv = 0.1 mrem

**Common Prefixes for SI Units**

<table>
<thead>
<tr>
<th>Submultiples</th>
<th>Multiples</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-3} milli m</td>
<td>10^{3} kilo k</td>
</tr>
<tr>
<td>10^{-6} micro µ</td>
<td>10^{6} mega M</td>
</tr>
<tr>
<td>10^{-9} nano n</td>
<td>10^{9} giga G</td>
</tr>
<tr>
<td>10^{-12} pico p</td>
<td>10^{12} tera T</td>
</tr>
</tbody>
</table>

Source: Reference 47
Physical Aspects of Production of Ionizing Radiation

**Electromagnetic Radiation (X-rays, Gamma Rays, Bremsstrahlungen, Cosmic Electromagnetic Rays)**

Any photon produced as a result of a transition from a higher energy level to a lower energy level in a bound atomic structure has an energy characteristic of the energy difference in the shell of that atom. Optical energy transitions produce scintillation spectra with characteristic wavelengths. When the transition energy of the characteristic photons occurs in the ionizing energy region, then the photons are ionizing and are termed characteristic X-rays. Characteristic X-ray production occurs in materials of high Z and competes with another process called the Auger process, which predominates in materials of low Z. The letter “Z” refers to the number of protons and is defined in the next section. The Auger process is initiated in the same manner with the removal of a lower energy electron in an atom; however, the potential energy differential is not produced as a photon but imparted to an atomic electron passing in the vicinity of the transitional electron. At ionizing energy this unsuspecting electron is ejected from its shell in the atom with the ionizing kinetic energy of the transition minus the binding energy of the particular shell. The kinetic energy of the Auger electron is characteristic of the atom and can be statistically predicted.

The nomenclature in Table 23.4 evolved over the recent history of physics. The first column gives the common name of the radiation quality; the second whether the radiation is a particle or a photon; the third gives the atomic mass unit (AMU) to one significant figure. The origin column shows where each item is found in the atom: (1) the nucleus, the nuclear component governed by the nuclear force, which includes protons and neutrons among others; or (2) the atomic component, which comprises the electrons and its electron shell structure. The quality factor (QF) of low, medium, or high is listed so that the relative importance of biological interaction can be compared.

Some items mentioned are physically the same but their origins and common names are different. X-rays, gamma rays, and bremsstrahlungen are ionizing photons with a specified energy. Electrons and beta particles are particles with a rest mass of 0.511 MeV with a negative charge; positive betas and positrons are positive electrons with a rest mass of 0.511 MeV bearing a positive charge. The kinetic energy must be specified to compare them. The term “nucleon” refers to either a proton or a neutron.

### Table 23.4 — Category of Ionizing Rays

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Nature</th>
<th>AMU</th>
<th>Charge</th>
<th>Origin</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>nucleus</td>
<td>low</td>
</tr>
<tr>
<td>X-ray</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>atomic</td>
<td>low</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>atomic</td>
<td>low</td>
</tr>
<tr>
<td>Cosmic (EM)</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>extraterrestrial</td>
<td>low</td>
</tr>
<tr>
<td>Cosmic particle</td>
<td>particle</td>
<td>A</td>
<td>2+</td>
<td>extraterrestrial</td>
<td>high</td>
</tr>
<tr>
<td>Alpha</td>
<td>particle</td>
<td>4</td>
<td>1-</td>
<td>nucleus</td>
<td>high</td>
</tr>
<tr>
<td>Beta</td>
<td>particle</td>
<td>-0</td>
<td>1+</td>
<td>nucleus</td>
<td>low</td>
</tr>
<tr>
<td>Positive beta</td>
<td>particle</td>
<td>-0</td>
<td>1+</td>
<td>nucleus</td>
<td>low</td>
</tr>
<tr>
<td>Positron</td>
<td>particle</td>
<td>-0</td>
<td>1+</td>
<td>atomic</td>
<td>low</td>
</tr>
<tr>
<td>Electron</td>
<td>particle</td>
<td>-0</td>
<td>1-</td>
<td>atomic</td>
<td>low</td>
</tr>
<tr>
<td>Neutron</td>
<td>particle</td>
<td>1</td>
<td>1+</td>
<td>nucleus</td>
<td>middle/high</td>
</tr>
<tr>
<td>Proton</td>
<td>particle</td>
<td>1</td>
<td>1+</td>
<td>nucleus</td>
<td>middle/high</td>
</tr>
<tr>
<td>Nucleon</td>
<td>particle</td>
<td>1</td>
<td>1+/0</td>
<td>nucleus</td>
<td>high</td>
</tr>
</tbody>
</table>

(a) Has mass
(b) Has charge

### Table 23.5 — Shorthand Notation of Common Nuclides

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Equivalent Symbol</th>
<th>Other Equivalents</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>$^1\text{H}$</td>
<td>hydrogen ion</td>
</tr>
<tr>
<td>α</td>
<td>alpha</td>
<td>$^2\text{H}$</td>
<td>doubly charged helium ion</td>
</tr>
<tr>
<td>d</td>
<td>deuteron</td>
<td>$^3\text{H}$</td>
<td>heavy hydrogen</td>
</tr>
<tr>
<td>t</td>
<td>triton</td>
<td>$^3\text{H}$</td>
<td>radiohydrogen</td>
</tr>
</tbody>
</table>

Notes: 1 amu = 1 proton = 931 MeV; 1 beta particle = 1 electron = 0.511 MeV. Water has the chemical formula H₂O. If one of the hydrogen atoms is the deuteron, then it is called deuterium and abbreviated as D₂O. If one of the hydrogen atoms in the water molecule is triton, then the water is called tritium, which happens to be a weak beta emitter and is used as a tracer.

### Table 23.6 — Quality Factor

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, electrons, betas</td>
<td>1</td>
</tr>
<tr>
<td>Thermal neutrons (&lt;10 keV)</td>
<td>3</td>
</tr>
<tr>
<td>Neutrons (&gt;10 keV)</td>
<td>10</td>
</tr>
<tr>
<td>Protons</td>
<td>10</td>
</tr>
<tr>
<td>Alpha</td>
<td>20</td>
</tr>
<tr>
<td>Heavy recoil nuclei</td>
<td>20</td>
</tr>
</tbody>
</table>

Radioactivity

Ionizing radiation is defined as the spontaneous emission of ionizing particles and/or ionizing photons (or gamma) from a nucleus. The nucleus consists only of protons, neutrons, and a pion, the exchange particle, which works in relation to the nuclear force. Charge is considered to be integral to the proton as the fundamental stable building block. The nucleus of an atom contains a specific combination of nucleons (proton or neutron) attracted by the nuclear force operating through the pion. The attractive nuclear force is the strongest force in nature, overcoming the Coulomb repulsion of the positive protons, and is charge independent, attracting equally either the proton or neutron. This force extends over a finite short range (~10–15 m=1 fm). The nucleons obey the Pauli exclusion principle, allowing two protons of opposite spin and two neutrons of opposite spin to fill one energy level.

To define a specific nucleus, the number of protons, the number of neutrons, and the energy levels of the nucleons must be specified. Stable nuclei have protons and neutrons in the ground state. The organization of nuclides by number of protons and number of neutrons is represented on the chart of the nuclides and contains currently known nuclei, stable and radioactive. A copy of the chart of nuclides can be found in the book, Atoms Radiation and Radiation Protection (2nd ed.).

The basis for the AMU on the chart of the nuclides is the carbon-12 (12C) nucleus. To account for binding energy, 1 AMU is defined as one-twelfth of the mass of a 12C nucleus, so that to one significant number the proton and the neutron each have a mass equal to one. The neutron/proton (n/p) ratio of 12C is 6/6=1; the nucleus is even/even, binding energy per nucleon is ~7.5 MeV, and the shell level is closed.

The atomic number is called the Z of the nuclide. The Z also can be represented by the chemical symbol with the atomic number written in the lower left corner. The range of atomic numbers from Z=1 to Z=109 can be broken roughly into three groups: low Z, where Z ranges from 1 to 20; mid-Z in the range 21-82; and high Z, greater than 82. The mass number of the nuclide is represented by the summation of the number of protons and number of neutrons and written in the upper left corner of the chemical symbol or the Z. A note here on nomenclature: to refer to one specific nucleus is to refer to a nuclide, not an isotope. An isotope is one nuclide of two or more nuclides with the same atomic number but different mass. If the entity is radioactive, then reference is made to the radionuclide. Each nuclide has its own mass number (A) represented by integers. Atomic weight refers to the number with four decimal places on the periodic table that is the weighted average of naturally occurring masses (isotopes) of a particular element.

The nucleons, similar to the electrons in the atomic structure, are each bound with a typical nuclear binding energy per nucleon of about 8 MeV. The larger the binding energy per nucleon, the more stable the nucleus. Stable nuclei tend to be symmetrical in number and parity. For stability the ratio of neutrons to protons for low Z nuclei is one, and the number of protons and neutrons is an even number. As the Z number increases, the size of the nucleus increases, and the trend for stability is to have more neutrons than protons. The Coulomb repulsion becomes significant at large numbers (n/p ~1.5 for stability). There is a point at which the nucleus is too large for stability (Z>83 and A>150), and those nuclides are radioactive.

Each of the radioactive decay processes that follow results in a lower energy nuclide, which may or may not be stable. The measure of radioactivity, the rate of decay, is the becquerel (1 disintegration per second) independent of the energy of the decay product. The time to decay to one-half of the initial activity is the physical half-life, typical of the original nucleus. Short half-lives are typical of highly unstable nuclei; long half-lives, of quasi-stable nuclei. The energy of the decay product is characteristic of the specific nuclide and is found in published documents. Decay may or may not end in a stable nuclide. High Z nuclides may decay through a series of decay radionuclides to stable nuclides.

If the physical half-life of the initial nuclide (parent) is longer than that of a radioactive decay nuclide (progeny), then an equilibrium condition can exist. If the half-life of the initial decay nuclide is very much greater than the decay nuclide (e.g., 226Ra of 1622 years to 222Rn of 3 days), a condition called secular equilibrium exists. For two nuclides with approximately equal half-lives, transient equilibrium exists (e.g., 222Pb of 10.6 hours to 212Bi of 1 hour). These equilibria occur under closed conditions. If the half-life of the progeny exceeds that of the parent, no equilibrium is possible.

Gamma Decay

Gamma ray emission occurs from natural background and manmade sources. The gamma ray is a photon (no mass and no charge, and spin=1) emitted from a nucleus when a nucleon makes a transition from a high energy level to a lower one. After emission of a gamma (γ), the energy of the nucleus is less.

Pure gamma emission occurs when only a gamma is emitted; atomic number and mass remain the same.

\[ ^{43}\text{Nb} \rightarrow ^{43}\text{Nb} + \gamma \]  

(1)

Isomeric transition occurs if the nucleus stays in an excited state longer than 10^6 sec and less than 24 hours. The two nuclides are isomers of each other, each being a different nuclide. The mass number of
the initial radionuclide is accompanied by an “m” for metastable and always must be expressed. A metastable nuclide at the higher energy will always decay by isomeric transition, emitting a gamma. The product may or may not be stable.

\[
^{99m}\text{Tc} \rightarrow ^{99}\text{Tc} + \gamma \tag{2}
\]

Internal conversion occurs when a nucleon has a higher than normal energy state. The nucleon makes a transition to a lower energy state by giving off the energy to an electron (rather than emitting a gamma). Most probably the K-shell electron receives this energy and is ejected from the atom with the energy of transition from the nucleus minus the K-shell electron binding energy. The electron is monoenergetic and is termed the conversion electron. An excited nucleus can branch between gamma decay and internal conversion. This nuclear process is analogous to the branching between characteristic X-rays and the Auger process in the photoelectric effect. The electron behaves identically to a beta particle and warrants similar health physics controls.

\[
^{131}\text{Xe}^* \rightarrow ^{131}\text{Xe} + e \tag{3}
\]

Beta/gamma emission occurs almost simultaneously when a beta is emitted from a nucleus. See the section on Isobaric Transitions.

Excited state emission occurs when a nucleon is momentarily in a higher energy level and decays in less than 10⁻⁶ sec to the ground state. The excited state is indicated by an asterisk to the upper right of the Z.

\[
^{14}\text{C}^* \rightarrow ^{14}\text{C} + \gamma \tag{4}
\]

The difference between the excited state, isomeric state, and gamma emission state is the length of the half-life. Normal use of radionuclides relies on the half-lives being long enough to be measurable after the creation of the radionuclide. Knowledge of excited state radiation is important for developing shielding requirements near cyclotrons and accelerators, but such radiation occurs so rapidly that it is not important in the use of sealed sources. The isomeric transition of 99mTc is the workhorse of nuclear medicine departments for medical imaging of radionuclides. The half-life of 6 hours is long enough to perform a medical procedure and short enough to decay rapidly to reduce body burden.

**Isobaric Transitions**

A beta (β or β⁺) particle is a high kinetic energy electron of nuclear origin possessing a charge of plus or minus 1, the mass equivalent of an electron (0.511 MeV), and a spin of one half. Emission of a beta particle makes the transition isobaric because the mass of the radioactive product is essentially the same as the mass of the radioactive nuclide that emitted the beta. A beta particle emitted in an isobaric transition is not monoenergetic but ranges between zero and a maximum value. Its kinetic energy plus that of its companion, the neutrino, maintains the conservation laws (of energy and spin). The neutrino is a particle with no mass that travels at the speed of light, is almost undetectable, and is not of interest for purposes of radiation protection but is presented here to balance the mass/energy equations. Beta decay changes the n/p ratio toward stability and can result in a stable nucleus, which occurs most frequently in beta decay of low Z. The beta/gamma decay predominates over other decay modes with nuclides in the middle Z range.

(Negative) beta decay is a process initiated by an imbalance in the nucleus, which has too many neutrons in comparison with the number of protons. The n/p ratio is too large (>1 for low Z) for stability. Effectively, a neutron is converted into a proton, reducing the ratio toward stability. This process of beta decay occurs in naturally occurring radionuclides and fission products.

The following decay process occurs whenever a neutron is converted to a proton and also when the neutron is free from the nuclear force.

\[
^0\text{n} \rightarrow ^1\text{p} + \beta^- + \nu \tag{5}
\]

An example of pure beta emission is as follows.

\[
^{32}\text{P} \rightarrow ^{32}\text{S} + \beta^- + \nu \tag{6}
\]

A neutron in the nucleus is converted into a proton, a beta particle, and an antineutrino. The beta particle and the antineutrino are emitted, leaving the nucleus with the same mass (isobaric transition).

If the decay creates a nuclide in an excited state, the subsequent very rapid decay of the progeny nucleus can emit one gamma or multiple gammas. The transition occurs in an immeasurable time, so the transition is written as one equation.

\[
^{60}\text{Co} \rightarrow ^{60}\text{Ni} + \beta^- + n + \gamma_1 + \gamma_2 \tag{7}
\]

The beta/gamma transitions predominate over pure beta in the mid-Z range.

Positive beta decay is a process initiated by an imbalance in the nucleus caused by too many protons in comparison with the number of neutrons. The n/p ratio is too small for stability and is increased toward stability when a proton is converted into a neutron. Positive beta radionuclide emitters do not normally occur in nature and must be produced on cyclotrons or accelerators. Positive beta radionuclides are used in medicine for diagnostic applications.

The net process that occurs in the nucleus is shown in the following equation.

\[
^1\text{p} + \rightarrow ^0\text{n} + \beta^+ + \nu \tag{8}
\]
An example of a pure positron emitter would be

\[ ^8\text{B} \rightarrow ^3\text{Be} + \beta^+ + \nu \]

Similar to negative beta/gamma decay, in positive beta/gamma decay a positive beta is emitted from the nucleus followed by the gamma emission.

\[ ^{68}\text{Ga} \rightarrow ^{68}\text{Zn} + \beta^+ + \gamma_1 + \gamma_2 + \nu \]  \hspace{1cm} (9)

With the emission of a positive beta particle there is always a secondary radiation reaction called annihilation radiation. The positive beta encounters an electron in the medium. The two annihilate one another by converting the rest mass of the two particles into two photons of 0.511 MeV each, traveling in opposite directions (180° or π radian).

\[ \beta^+ + e^- \rightarrow \gamma + \gamma \]  \hspace{1cm} (10)

The medical profession uses PET (positron emission tomography) as a diagnostic tool based on the detection of the annihilation radiation. Radiation protection for personnel working in this field must address potential exposures to the radioactive nuclide, such as fluorine-18, as well as the annihilation radiation that results from the decay. This is the same annihilation radiation as in the attenuation process of pair production.

Electron capture competes with positive beta decay. The effect of the decay process is the same; the proton is converted into a neutron, rendering the transition isobaric with a net decrease of one in the Z number. The excited nucleus captures an electron from the atomic structure, usually a K-shell electron. The electron at nuclear force range combines with the proton to form a neutron. There is, of course, a “hole” in the lower levels of the atomic structure whereby secondary radiation can occur.

\[ ^1\text{p} + e^- \rightarrow ^1\text{n} + \nu \]  \hspace{1cm} (11a)

\[ ^{67}\text{Ga} + e^- \rightarrow ^{67}\text{Ni} + \nu \]  \hspace{1cm} (11b)

**Alpha Decay**

The alpha (α) particle consists of one shell level of a nucleus, two protons, and two neutrons at nuclear distances. For a high Z radionuclide less energy is required to dump an entire shell of four nucleons than to emit a single particle. Alpha decay results in a nuclide with an atomic number less by two AMU and a mass less by four AMU than the original nucleus. The n/p ratio after emission usually does not result in forming a stable nucleus. The alpha is monoenergetic, with energy in the MeV range, and occurs only in heavy nuclei, Z>82 and A>150. After emission the alpha has a limited range in matter because of its large double charge and large mass. (In equations, the mass and Z of the alpha are not normally written.)

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^{4}\text{He}^{++} \]  \hspace{1cm} (12)

Alpha emitters are routinely used in the medical area. There are some industrial product uses in moisture gauges, static electrometers, and smoke detectors. It is now problematic to dispose of the smoke detectors. It is suggested that any product that contains an alpha emitter be stored until the disposal procedures are checked. Even though initially unlicensed, some of these items must now have disposal records traceable to an approved site. Table 23.7 provides a profile of the characteristics of ionizing radiation.

**Dosimetry**

**Attenuation Processes**

For both particles and photons the incident ray can interact elastically or inelastically. The word *scattering* is misused. In the strictest sense it applies to interactions of either photon or particle origin in which an incident ray is changed in direction with or without an energy loss. In inelastic scattering, energy is imparted from the ray to the medium. Scattering does not apply to secondary processes such as characteristic X-ray production or annihilation radiation. Photons are attenuated exponentially; particles are attenuated to a finite depth.

**Attenuation of Photons**

The following processes are organized into two major groups—interactions without energy deposition and interactions with energy deposition. The conservation laws of physics governing all interactions are not explicitly stated. Processes in which a reduction in intensity of a beam, particles, and/or photons is known but energy transfer is unknown is termed attenuation. For those processes relating to energy transfer from the beam to the medium, then the word *absorption* can be applied. For the majority of radiation dose processes applicable to humans (the photoelectric and the Compton effect from medical sources and background) the photon interacts with an electron within the body. It is sufficient to state that the photon must interact with an electron attached to an atom, ion, or radical and not with a free electron. A free electron is one not bound in an atomic structure and that can have energy or momentum equal to zero.

**Elastic, Classical, or Unmodified Scatter for Photons**

The energy of the photon after scattering is the same as before the scattering. Therefore, the frequency and the wavelength remain the same. The only difference is that the direction of travel probably changes. At the atomic level the photon is absorbed and reemitted at the same energy. There
is a chance that it can be emitted in the same general direction, called forward scatter. Elastic scattering is less probable in the ionizing range than in the nonionizing region of the electromagnetic spectrum, and its probability diminishes with an increase in photon energy. See the discussion of the Compton effect later in this section for inelastic or modified scattering.

**Absorption Process for Photons: Photoelectric, Compton, Pair Production, and Photodisintegration**

For an ionizing photon (E>10 keV) the most probable process of interaction in matter depends on its energy. Low-energy photons are those with energies between 10 and 50 keV; medium energy photons those with energies from ~100 keV to ~10 MeV; and high-energy photons are those with threshold energies beginning at 1.02 MeV, but predominate at energies greater than 10 MeV. The electrons released or created in these interactions deposit energy, which is the ionizing radiation dose. The specific names for these interactions apply to photon interactions only and not to nuclear interactions.

For photons whose energies begin at the ionization energy to about 125 keV, the photoelectric effect is the predominant absorption process. The photoelectric effect, also called a total absorption process, occurs when an inner shell electron of an atom absorbs the energy of an incident photon. The energy of the photon must exceed the binding energy of the electron. The electron is ejected from its shell with the kinetic energy of the initial photon minus the binding energy of the particular shell. The electron deposits its energy within a local region of where it was released. This energy is the dose deposited from the primary interaction and is specifically called the photoelectron. After the initial removal of an inner shell electron to become the photoelectron, an outer shell electron quantum mechanically moves to fill in the space of the ejected photoelectron. This transitional electron must release excess energy in the process of moving to a lower energy level. The release of its energy is considered a secondary process. The original atom becomes an ion and will eventually collect an electron to balance charge after a secondary process has occurred.

There can be two secondary processes from the primary photoelectric effect. These two processes statistically compete with each other depending on the atomic number of the target atom. The fluorescent yield is the fraction of secondary photons (characteristic X-ray production) compared with the secondary electrons (Auger process) created in the secondary process subsequent to the photoelectric effect.

For atoms of low atomic number the Auger electron emission predominates. The Auger electron is one of the atomic electrons selected to be given the energy from the transitional electron. Statistically, the Auger electron originates from the same atomic shell as the photoelectron. Given the shell level, this energy is predictable and is considered monoenergetic. Most detectors measure photons and not electrons and would not measure the energy of this electron, but this secondary electron contributes to human dose.

For atoms with high atomic number the excess energy from the transitional electron appears as a photon (or photons) equal in energy to the shell(s) of transition. In high-Z material such as tungsten, copper, materials used in shielding, and target material, these photons have energies in the ionizing region and are termed characteristic X-rays. They are characteristic energy of the atomic shell, and, therefore, of the element (Z) creating them and are X-rays from creation by electrons. These X-rays are attenuated as any other ionizing photon. Any condition removing an inner shell electron from an atom induces a similar secondary effect of characteristic X-ray(s) or the Auger electron process. Auger electrons are produced in some radioactive decay processes and become important for hand and eye dosimetry in the use of radioactive materials. Protective lenses and gloves not only protect against contamination but also offer an absorption barrier for electrons and beta particles.

The photoelectric effect is the principle attenuating process underlying use of diagnostic X-rays and dental films. The Z-cubed dependence of the absorbing medium for the same energy photons allows a differential absorption of the incident

<table>
<thead>
<tr>
<th>Photon</th>
<th>attenuation is exponential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>monoenergetic gamma from radionuclides</td>
</tr>
<tr>
<td></td>
<td>bremsstrahlung or X-rays from machines</td>
</tr>
<tr>
<td></td>
<td>can compare energy of different photons by HVL</td>
</tr>
<tr>
<td></td>
<td>radionuclides emitting gamma have specific gamma factor</td>
</tr>
<tr>
<td>Alpha particle</td>
<td>always monoenergetic</td>
</tr>
<tr>
<td>Beta (positive &amp; negative)</td>
<td>not monoenergetic</td>
</tr>
<tr>
<td>Neutrino</td>
<td>not important for dosimetry</td>
</tr>
</tbody>
</table>

Note: HVL = half value layer.
photon has 0.511 MeV of energy each and travels in opposite (180° or π radian) directions from one another.

Any two particles with the same mass but opposite charge and angular momentum are termed antiparticles of each other. Examples include antiprotons and antineutrons.

Annihilation radiation is a process that necessarily follows any particle-antiparticle annihilation process, releasing photons with the mass-equivalent energies. The most common one is the 0.511 MeV positron-electron interaction. Annihilation radiation is used in some nuclear medicine procedures. Rather than use a positron to interact with an electron, a positive beta is created by selecting the appropriate radioactive material to yield a positive beta. Positive betas and positrons differ only in nomenclature relating to their origin. The 0.511 MeV photons are measured with coincidence counters.

Photodisintegration completes the attenuation processes for photons. An incident photon with a threshold energy ~8 MeV or greater interacts with the nucleus of an atom emitting a nucleon or a combination of nucleons. One exception is 9Be with a threshold energy of 1.66 MeV for a gamma-ray, neutron-out reaction. With a high threshold and low probability of interaction this process is limited to high-energy machines in research.

**Attenuation of Particles**

There are similarities between the attenuation of free particles and attenuation of photons in matter. Both have an associated wavelength, the deBroglie wavelength, and are characterized by energy. However, the differences are greater than the similarities. Photons are exponentially attenuated; particles deliver the energy, the dose, in a finite, short range. Particles created on cyclotrons or accelerators, of course, will have a long range. Photons carry no charge; most particles are charged. Even the uncharged neutron free from the nucleus will decay into two charged particles.

**Charged Particles**

A charged particle loses energy in a medium proportional to charge and to mass, and inversely proportional to its velocity squared. If the particle is created by a radioactive decay process, its maximum energy is predictable.

Monoenergetic charged particles display the Bragg peak when dissipating energy in matter. The most common example is the alpha particle. As the particle slows down and spends more time
per path length, the curve increases in ionizing density and terminates at a predictable depth dependent on the density of the attenuator and kinetic energy of the alpha. Because of its large mass and double positive charge, an alpha particle is limited to a very short range. In air the typical 5 MeV alpha has a range of 5 cm and in skin is attenuated by the dead layer. Internally, alpha particles are a serious biological hazard particularly to the lung and other organs and tissues to which the radionuclides are biochemically transported. See the section on radon later in this chapter.

The beta (negative) or positive beta is emitted in radioactive decay with its companion neutrino sharing the total energy and is not monoenergetic, only statistically predictable. The kinetic energy of the beta varies between zero and a maximum value. The neutrino, the energy of which varies between the maximum value and zero, is not considered interactive with matter and is ignored for radiation protection purposes. Beta particles created from radioactive decay are listed according to an average energy, approximately one-third the maximum energy. Beta particles and free ionizing electrons deposit energy in tissue to a depth of 0.5 cm for each MeV. A 10-MeV electron (or beta) will penetrate the skin to about 5 cm.

**Noncharged Particles**

**Neutrons**

The topic of neutrons is added for completion. With no net charge a neutron can interact with target nuclei by being captured by the target nucleus to create, in most cases, an unstable nuclide. This process is known as neutron activation and serves as the beginning of artificially produced radionuclides. The activated isotopic nuclide provides a beta/gamma emitting product. If in the process of capture a particle is ejected, the newly formed nuclide is transmuted into a new element. Neutrons are part of the process that provides fission of a uranium nucleus and are an important radiation protection consideration.

Free neutrons occur in nuclear facilities, where fission and neutron activation are of interest. There are no pure neutron emitters; $^{252}$Cf is a close approximation with some gamma emission. Free neutrons are considered radioactive with a half-life of about 10.4 minutes. Their interaction can be either elastic scattering (fast neutrons with energy $>100$ keV) or inelastic, in which a small fraction of the neutron energy is transferred to the target, resulting in gamma emission (medium energy of 100 eV-100 keV; slow 0.025-100 eV). It is the thermal neutron with kinetic energy of the order of room temperature $\sim 0.025$ eV that undergoes capture.

The objective in neutron radiation protection is to reduce the energy of the high-energy neutrons by inelastic scattering and then capture them with an appropriate nucleus. Materials to thermalize neutrons are made from low Z materials such as water, plastic, or paraffin. Capture is then accomplished by boron or cadmium. Protection from secondary radiation is provided by specially selected materials impregnated in the protective shielding. Neutron dosimetry is complex, and measurement involves special neutron detectors.

A summary of relative attenuation due to energy and atomic number of the attenuator appears in Table 23.8. The energies of the attenuation processes are in Table 23.9.

### Radiation Measurements

#### External Monitoring

Radiation detection devices detect and/or measure the radiation dose from a field of radiation. Selection of the appropriate detector is critical in the evaluation of the radiation dose or dose rate. The sensitive volume is that part of the detector where interaction between the radiation and the detection medium actually occurs. Survey devices or equipment consist of portable, multiscaled radiation detectors to evaluate radiation dose over a relatively short period of time (usually dose per minute). Survey instruments can operate on batteries, be light enough for an adult to carry in one hand, and respond in multiple ways to radiation fields. Many have audio speakers in addition to multistaged scaling factors, and some can measure particles and/or photons.

Monitoring devices evaluate a radiation field over a relatively long period of time (week or month). Personnel monitors generally are evaluated monthly. Personnel who require shorter time evaluation wear special monitors. Room monitoring equipment may be active continuously with threshold warning devices in Table 23.10 provides

### Table 23.8 — Summary of Attenuation Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Z</th>
<th>Energy</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic scattering</td>
<td>-</td>
<td>$1/E$</td>
<td>entire EM spectrum</td>
</tr>
<tr>
<td>Photoelectric effect</td>
<td>$Z$</td>
<td>$1/E^3$</td>
<td>K binding energy of Z</td>
</tr>
<tr>
<td>Compton effect</td>
<td>independent</td>
<td>$1/E$</td>
<td>—</td>
</tr>
<tr>
<td>Pair production</td>
<td>$Z$ or $Z^2$</td>
<td>$E$</td>
<td>incident photon of 1.02 MeV nuclear binding energy</td>
</tr>
<tr>
<td>Photodisintegration</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 23.9 — Process by Which Ionizing Radiation is Absorbed in Soft Tissue

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Attenuation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-50 keV</td>
<td>photoelectric much more than Compton</td>
</tr>
<tr>
<td>60-90 keV</td>
<td>photoelectric and Compton equally</td>
</tr>
<tr>
<td>100-200 keV</td>
<td>Compton more than photoelectric</td>
</tr>
<tr>
<td>200 keV-2 MeV</td>
<td>Compton alone</td>
</tr>
<tr>
<td>2-5 MeV</td>
<td>Compton and some pair production</td>
</tr>
<tr>
<td>5-50 MeV</td>
<td>pair production begins to predominate</td>
</tr>
<tr>
<td>&gt;50 MeV</td>
<td>pair production most important</td>
</tr>
</tbody>
</table>

Note: Water $Z \sim 7.4$. 
an overview of most of the radiation detectors in health physics application; Table 23.11 gives more detail on the common survey methodologies.

Ionization and excitation are the fundamental interaction processes that provide the basis for the operation of radiation detectors. Detectors operate in either counting mode or spectroscopy mode. In either case, radiation transfers energy to the detector, which is connected to a high-voltage power supply. The interaction of ionizing radiation with the detector produces pulses of energy (one for each interaction), which are sent to a processor (e.g., amplifier or discrimination). Once the pulses are shaped and accepted, they are counted using either a scaler or rate meter. Rate meters, however, are commonly associated with survey and not laboratory instrumentation.

The basic distinction between counting and spectroscopy is that detectors operating strictly in the counting mode will indicate that radiation is present, but will not be able to supply information as to the energy of the radiation and the identity of the radionuclide. Spectroscopy units, on the other hand, can analyze the height of the pulse and relate that height to the incident energy. Once that is determined, the identity of the source can be determined.

### Gas-Filled Detectors

There are three types of gas-filled detectors: Geiger counters or Geiger Mueller (GM) detectors, proportional counters, and ionization chambers. Each of these three detectors contains a central wire known as the anode that initially carries a positive (+) charge. Alpha and beta particle interactions inside the gas produce primary ion pairs. The electron component of the ion pair will be attracted to the anode. The positive member of the ion pair will be attracted to the outer wall, which is initially negatively (-) charged with respect to the anode. This outer wall is known as the cathode. Gamma ray interactions most often first occur with the outer cathode wall rather than the fill gas. These interactions eject electrons from the wall; the electrons, as charged particles, then ionize the gas as noted previously.

### Solid-Filled Detectors

There are three basic types of solid-filled detectors: sodium iodide, zinc sulfide (ZnS), and high-purity germanium. Sodium iodide detectors are crystalline solids that respond to gamma radiation by producing visible light flashes. Hence, they are known as scintillators. ZnS detectors are also crystalline solids useful for the detection of alpha radiation. They, too, rely on the scintillation process. In either case the light is converted into an electronic signal for recording purposes.

Detectors utilizing germanium are referred to as semiconductor or solid-state detectors. They are used exclusively for the detection of gamma radiation. Table 23.11 contains a summary of the types, uses, advantages, and disadvantages of radiation survey instruments that are commonly applied for licensed facilities.

### Instrument Use Considerations

Regardless of the instrument type, the following should be considered when using a radiation survey instrument:

- Select an appropriate survey instrument for the radionuclide/radiations of interest.
- Unless the instrument is being used strictly as a detection device, the instrument should be calibrated for the radionuclide and energy or energies of interest.
Calibration sources and devices should be traceable to the National Institute for Standards and Technology.

Background and operability checks (high voltage, battery, source checks, etc.) should be performed daily (often two to three times in the same day).

The ideal ionizing chamber displays an increase in ion pair production (quantity) with an increase in output voltage (quality) applied across the chamber. The response of the ideal chamber is not linear but has various regions. As the output voltage increases from zero, a threshold value of voltage is reached to produce an immediate rise in ion pair production at relatively low voltage to a plateau called the ionizing region. As the voltage increases beyond the plateau, the number of ion pairs produced is proportional to the applied voltage over that range. This region is called the proportional region and terminates in the limited proportion region. In this region the response of the chamber is relatively linear in shape and is energy dependent. The response of different energy particles and photons can be separated. At relatively high voltage the response of the ion pairs plateaus. The response in this region, the Geiger region, is fairly flat and terminates with a rapid rise in voltage, which will destroy the tube, the discharge region. See Figure 23.11 for the response curve. A radiation detector designed to operate in one and only one of these regions is called an ionization chamber, proportional counter, or Geiger counter, respectively. Selection of the instrument depends on application. Ionization chambers and Geiger counters are usually portable and used for surveys. Proportional counters measure mixed

<table>
<thead>
<tr>
<th>Table 23.11 — Radiation Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector</strong></td>
</tr>
<tr>
<td>GM detectors, end window, pancake</td>
</tr>
<tr>
<td>GM detectors, side window</td>
</tr>
<tr>
<td>Proportional counter, gas flow</td>
</tr>
<tr>
<td>Proportional counter, air</td>
</tr>
<tr>
<td>Sodium iodide scintillation detector</td>
</tr>
<tr>
<td>Zinc sulfide scintillation detector</td>
</tr>
<tr>
<td>Ionization chamber</td>
</tr>
</tbody>
</table>


Note: Appropriate calibration factor and/or instrument design required.
radiation fields such as might be found in environmental monitoring.

A radiation survey is performed to measure the radiation field; measure contamination levels, fixed or removable; and/or measure airborne radioactivity. For contamination survey instruments, the following additional considerations should be taken into account:

- Use the “fast” response on the instrument (if available) to achieve the highest detector sensitivity. The instrument response can be switched to the “slow” setting for recording purposes.
- Use headphones when available to detect increases in count rate by the audible meter output. This allows the surveyor to watch the probe and the surface being evaluated, rather than the meter itself.
- The speed at which the detector moves should be relatively slow, less than 3 inches per second. Accelerated movement of the probe can result in failure to detect the radioactivity. The experience of the surveyor aids in minimizing this potential problem. Typical scanning speeds are on the order of one detector width per second.
- Directional dependence of the probe may necessitate overlapping scanning intervals.

Removable radiation from liquid sources or fragments of radioactive particles is called contamination. If the lower level of the survey equipment lies within the measurability of the small amounts of radiation, then the equipment is capable of locating the contamination. Radioactive solid sources can flake, crack, or chip to release radioactive particles to the environment. Liquid sources can leak, drip, or spread with poor transfer technique to the work environment. Control of unwanted radioactive contamination is an additional consideration in the protection of personnel. Radioactive materials require U.S. Nuclear Regulatory Commission (NRC) licenses or state registration for use. Laboratories are required to survey periodically (daily or weekly) with instruments to detect the radionuclide. If the energy is too low for a standard survey meter (tritium or $^3$H; $^{14}$C) then wipe testing is required. The wipe test involves swabbing a 100-cm² area with a small swab (~2 cm²) and then measuring the activity with instruments that can detect the specific radionuclide. If, however, contamination occurs in a high radiation field such as a radiopharmacy (hot lab) where locked storage and current NRC postings are required, then the radiation surveyor wipes a defined area (10 cm × 10 cm) with an absorbent disposable cloth to measure that activity on an instrument outside the radiation field. Wipe tests and records to document the procedure are performed routinely as per license requirements. The swab may be wetted with a chelating agent. Certain radionuclides with low beta energy ($^{14}$C and $^3$H) require wipe tests with special instrumentation. The requirements for a specific laboratory or operation are described in the license issued by the NRC or an agreement state. Site specific limits are established in the license as well as the frequency for testing and completing radiation surveys.

The use of personnel dosimeters is one of the most important aspects of a radiation monitoring program. These devices not only detect but measure the amount of exposure. They permit radiation protection professionals to ensure not only personnel are not being exposed excessively, but also to demonstrate that regulatory dose limits have not been exceeded. Routine monitoring is an element of the radiation protection program and the philosophy to keep one’s radiation exposure as low as reasonably achievable (ALARA). (See section, ALARA Program, for more details.)

Regulatory requirements for the assessment and recording of external exposures are set forth by different federal agencies such as NRC and the Department of Energy (DOE). The armed services (Army, Navy, Marine Corps, Air Force, and the Coast Guard) have their own regulations that closely parallel those issued by NRC. In addition, many states have their own set of radiation protection regulations addressing this particular issue. NRC, DOE, and other radiation protection requirements were developed and are periodically revised to attain consistency with radiation-related guidance that has been submitted by the Environmental Protection Agency (EPA) to the president of the United States. This guidance is based on current recommendations provided by consensus standards organizations.

External exposures usually involve a derived or inferred quantity because directly measuring the dose (or energy imparted) to every organ or tissue in the body with extreme accuracy is not realistic. There are several important elements of external monitoring programs, all of which are necessary for their successful operation. For example,
the staff who operate the program must be well trained. In addition, the monitoring devices must be suitable for the radiation present at the facility, and their use parameters (deployment duration, position on the body, etc.) must be designed to ensure the measured result is representative of the true exposure. Finally, the records associated with the measurements and their interpretation are almost as important as the measurements themselves. Radiation measurements are provided using a system consistent with the metric system or the International System of Units (SI units). The International Commission on Radiation Units and Measurements has published units to correspond to each type of measurement. For example, a becquerel was defined as one disintegration per second. A sievert (Sv) was defined as 100 rem. Table 23.3 lists each of the SI units and the corresponding conversion factor. In this text the SI unit is provided as well as the conventional radiation units, defined before 1975. The NRC issued a policy statement in 1992 requiring licensees to report surveys and dose assessments using the SI units. In practice, the conventional radiation units are still used today by many health physicists in the United States.

Personnel monitoring devices, sometimes called personnel dosimeters, are essentially devices designed to be worn or carried by an individual for the purpose of measuring the exposure he or she receives. One of the most popular types of monitoring devices contains small chips of a salt called thermoluminescent dosimeters, or TLDs. Another type that contains film similar to the film used by a dentist for X-raying teeth is called a film badge. Both of these types of monitoring devices require processing before the data are available. Primary personnel monitoring devices—that is, those typically used for the official measurement of the exposure received for record-keeping purposes—include TLD and film badges. A TLD can contain a variety of different materials. When these materials are exposed to radiation, the absorbed energy is “trapped” and held indefinitely. When the materials are heated (the basis for the “thermo” part of the device name) at a later date in a device known as a TLD reader, the trapped energy is released in the form of light or luminescence. The amount of light is then related to the radiation dose. That the absorbed radiation energy is trapped indefinitely is a prime advantage because the user can decide when the TLD will be read and the results reported. It is not uncommon for a period of several months to pass between the radiation exposure and the read-out of the TLD.

Another advantage is that TLDs come in a variety of materials, sizes, and shapes. These dosimeters are small, light, easy to handle, and can be worn comfortably by the individual. They are capable of covering a wide range of radiation exposures, from less than a few thousandths of a sievert (millirem) to greater than 10 sievert (>1000 rem). In addition, they have applicability for environmental measurements as well—a situation made possible because certain types of TLDs are very sensitive to very low radiation exposures (the type of exposure levels found in the environment). A TLD can be read only once; that is, once the trapped electrons have been heated, the amount of light produced, and the results recorded, the TLD cannot be reread to confirm the results. It is also possible for a certain degree of “fading” to take place, whereby some of the trapped electrons leave their excited energy states and return to the ground state prior to being read. This potentially results in a lower estimate of the individual’s exposure. (Many TLD materials, however, do not have this problem, and for those that do, correction factors can be applied to account for this situation.) Finally, some TLD materials exhibit energy dependence, which means the TLD’s response depends on the energy of the radiation that interacted with it.

Personnel exposures to ionizing radiation may be monitored using X-ray film. The sensitive volume is the silver ion of either silver bromide or silver iodide. The percentage of AgI is about 10% to allow the atomic number of I (Z=53) to attenuate radiation by the photoelectric effect. Care must be taken in the handling and storage of unexposed film as results are highly dependent on processing controls, pressure, humidity, storage on edge and not flat, and artifacts by air pockets. Processing of exposed film must be done using standard conditions.

When properly developed, film displays an optical density increment with an increase of radiation exposure called the Hurter-Driffield curve. The curve displays a linear central portion, called the gradient or film gamma, which gives information on film contrast and film latitudes. Optical density (OD) is defined as the logarithm of base 10 of the ratio of the intensity of incident light divided by the intensity of transmitted light. There is always a minimum OD such that the curve does not go through the origin due to base fog, somewhere around 0.2 density units for film properly stored and within the shelf-life date. Good diagnostic quality lies in a range of OD 0.25–2.5 in increments of 0.02. The density of the film is read by a densitometer, which emits light through a processed film. A densitometer exposes undeveloped film to the known intensity of a known photon energy. The film is then processed to produce a calibration strip of known density (see Table 23.10).

Even though film is not as widely used as TLD-based devices, it still presents some important advantages. For example, unlike TLD, film can be read as many times as is desired to confirm or recheck prior results. In other words, the information contained on the film is not destroyed once it is read. This is an extremely useful feature when
questions arise regarding the exposure received by an individual. A second and equally important advantage is that the type of radiation that is exposed to the film (i.e., low-energy X-rays, high-energy X-rays, gamma radiation, neutron radiation) and the radiation energy can be determined. This is typically accomplished in two ways. First, the film is surrounded with a series of filters that cause various responses on the film depending on the type and energy of the radiation. Second, the film in the badge is compared with film that has been darkened by various well-characterized radiation types at different (but known) exposure levels. Film has the additional advantages of being small, light, easy to handle, and comfortable to wear; it can provide useful information over a wide range of radiation exposures; it can show whether an acute or chronic exposure to radiation occurred based on the appearance of the film; and it can determine the orientation of the exposure, that is, whether an exposure occurred from the front or the back of the badge. Interpreting the results from a piece of exposed film is not as easy as it sounds. Even though it can be interpreted and reinterpreted many years after the exposure occurred, the calibration films (i.e., those exposed to known sources of radiation) prepared at the time of the original exposure must be preserved. This occurs because film can fade if it is stored improperly, in the same manner as photographs may fade over time.

There are small instruments that function like gas-filled survey meters. These devices can be direct-reading, and provide real-time information about the accumulated exposure received, or they can “chirp” or make noise whenever the accumulated exposure reaches a predetermined level. Audible-alarm dosimeters and direct-reading pocket ionization chambers are examples of supplemental dosimetry devices often worn with or located near the primary dosimeter. The latter devices should not be used as the official record of the exposure received.

An alarming dosimeter contains a small GM detector and some electronics. Typically, the electronic circuit causes a series of “beeps” or “chirps” when the GM detector responds to radiation. If calibrated properly, the number of “chirps” can be made equivalent to a known amount of radiation exposure. For example, if the device is set to “chirp” every time the GM counter is exposed to 1 milliroentgen, a dosimeter that “chirps” five times during the next hour reflects an exposure of 5 milliroentgens. When these devices are used in industry, their primary purpose is to make noise when a preset exposure or exposure rate has been exceeded. As such, they serve as warning devices rather than as a true dosimeter to measure the exposure received. It is most important that the device be checked for functionality before work in a radiation field occurs. At that time, the device is typically preset to a specific alarm set point. However, it is equally important that the device be calibrated periodically to ensure the set points correspond to true radiation exposures. These dosimeters can create a false sense of security for workers, because they can malfunction. A dosimeter that has been dropped, has low batteries, or that is worn such that the GM detector inside cannot detect the radiation exposure serves little purpose. An alarming dosimeter should never be used as a substitute for a radiation survey instrument, for job preplanning, or for basic common sense.

A direct-reading dosimeter, also called a pocket meter or pocket ionization chamber, is a small air-filled instrument, typically the size of a short, fat pen. It operates on the principle of radiation ionizing air, and it is capable of responding, primarily, to photon radiation (i.e., gamma rays, X-rays) and sometimes to high-energy beta radiation. Specially modified direct-reading dosimeters also can be used to measure neutron radiation. A direct-reading dosimeter contains both a “fixed” and a “movable” quartz fiber. When the dosimeter is first put into use, an electrical charge is placed on both fibers. Because of their similar charge, the two fibers “repel” each other. As radiation enters the chamber and ionizes the air inside, the charge on the fibers is neutralized, and the fibers begin to move closer together. The degree of movement, which is proportional to the amount of exposure received, can be seen by observing one of the fibers through an eyepiece that is on the end of the device. And this is perhaps the greatest advantage of using a direct-reading dosimeter. A user can determine his or her exposure at any time by holding the pocket dosimeter up to a light source and directly reading the value off a numerical scale. This allows workers to keep track of the amount of radiation exposure received over each day’s work. The greatest disadvantage associated with these devices is that they are fragile. Simply dropping one of them can cause the two fibers to “discharge.” In addition, they can “leak” some of their charge, meaning the fibers inside the dosimeter move even though there is no radiation exposure occurring. Finally, if the user forgets to “charge” the dosimeter before use, the device serves no purpose. It is for these reasons that a film badge or TLD is almost always used in conjunction with a direct-reading dosimeter.

Personnel monitoring programs are designed and conducted at nuclear facilities for several reasons. Among these are protecting the health of personnel; identifying poor work practices; detecting changes in radiological conditions; verifying the effectiveness of engineering and process controls; meeting ALARA considerations; demonstrating compliance with regulatory requirements; and keeping adequate records. From a regulatory standpoint, personnel monitoring is required under certain conditions—typically when an indi-
individual has the potential to receive 10% of the regulatory exposure limit from occupational exposure (i.e., as part of his or her work). For facilities licensed by NRC, adult occupational workers must be monitored if they have the potential to receive a dose greater than 5 mSv/yr (>500 millirem/yr).

For minors and declared pregnant women, however, monitoring is required when the individual is likely to receive 0.5 mSv/yr (>50 millirem/yr). NRC has grown increasingly concerned about a group of individuals known as industrial radiographers (nonmedical). These individuals typically use megabecquerel (multi-curie) sealed sources of radiation to “radiograph,” “image,” or take X-ray pictures of pipes to examine the adequacy of welds and to perform related activities. For a variety of reasons these intense radiation sources can and have caused exposures in excess of regulatory limits. In some cases very serious overexposures that resulted in observable health effects occurred.

NRC has issued specific regulations that impose additional external monitoring requirements for radiographers. These regulations require radiographers and their assistants to wear a direct-reading pocket dosimeter and either a film badge or TLD. An alarming device also is required except for permanent radiography facilities where alarming/warning devices are in routine use. Records documenting external exposures received by workers are required by federal and state agencies. These records must be maintained to document compliance, and they must be retained until their disposition is authorized by the overseeing agency. Examples of required records include those related to results of individual external exposure measurements; documentation of occupational exposures received during both current and prior years; data necessary to allow future verification or reassessment of recorded exposures; results of surveys, measurements, and calculations used to determine individual occupational exposures; results of maintenance and calibration performed on personnel monitoring devices; training records; results of internal audits; and declarations of pregnancy. Reports are required including, but not limited to, radiation exposure data for monitored individuals and records of exposure for terminating employees. In addition, an annual radiation dose report (NRC Form S) must be provided in writing to each individual who was monitored over the past year.

Potential exposure to “hot particles” is evaluated differently from whole-body or extremity exposures. Only the exposure to a small area on the anterior region of the body is evaluated as a measure of the whole-body exposure. The possibility exists that other more localized areas could have been highly exposed. If an overexposure occurs, it may be necessary to reconstruct the exposure situation (never the preferred method). A prime example is the occurrence and detection of so-called hot particles, also known as fleas or specks, at nuclear facilities (primarily nuclear power plants) around the country. Originating primarily from defects in the cladding surrounding reactor fuel elements or activation of Co-59 in the core, microscopic particles of very high specific activity are formed and can attach to clothing or exposed areas of the body. These hot particles are electrically charged and can therefore “hop” from one location to another, potentially resulting in highly localized, nonuniform beta/beta-gamma exposures. In sum, the advent of more sensitive radiation survey equipment has created the ability to detect these particles, but at the same time, the appearance of hot particles has become a challenge from a personnel monitoring standpoint.

Several of the major radiation protection regulations (e.g. 10 CFR Part 20 and 10 CFR Part 835) do not mandate where personnel monitoring devices should be located on the worker. However, assistance in this regard can be found in other radiation-related guidance documents. To determine the whole-body exposure, dosimeters should be placed on the trunk of the body (between the neck and the waist) and positioned so that the front of the badge holder is facing the source of the radiation. The dosimeter should be attached to the anterior portion of the torso. Dosimeters should not be attached to loose-fitting clothing, lapels, or worn on neck chains. Exposure to the lens of the eye is one concern for radiation protection professionals, and there is a separate regulatory limit for the eyes. For uniform exposures a measurement at the surface of the torso is usually assumed to be equivalent to the exposure in the location of the eye. Nonuniform exposures, however, which include localized beams of radiation, X-ray machines, or beta sources, require the placement of a dosimeter somewhere near the eyes. Typically, a dosimeter is mounted on the side of the head or on the forehead, such that it is located adjacent to the eye. Another circumstance is estimating the radiation exposure to the embryo/fetus of a pregnant worker. Again, wearing a conventional whole-body personnel dosimeter (e.g., TLD or film badge) between the neck and the waist typically provides an adequate result. However, in the case of nonuniform fields or when exposures begin to approach the applicable exposure limit, an additional dosimeter is mounted near the mother’s waist area or abdomen. The arms below the elbow and the legs below the knee are defined as extremities. Like the eyes, the extremities have a specific regulatory exposure limit. The limit is much higher than the limit for the whole body because there are few blood-forming organs in the extremities; thus, they are less sensitive to radiation exposure. When monitoring the exposure of the extremities, dosimeters are typically placed at the most exposed portion of the body. Ring badges, wrist badges, toe badges, and ankle badges that are custom-designed to provide as little movement restriction as possible are readily available for this purpose.
The National Voluntary Laboratory Accreditation Program, abbreviated NVLAP, provides accreditation for personnel dosimetry programs. The NVLAP accreditation process is designed to assess how precise and how accurate the devices are and how competent the processor is in providing the service. Competence, as used here, requires not only that the dosimeters perform adequately, but also that the processor demonstrates it has the staff, facilities and equipment, procedures, records and reports, and a quality assurance program to ensure reliable results. Any facility that provides personnel monitoring services is afforded the opportunity to attain accreditation. NVLAP accreditation is valid for 1 year, and must be verified each subsequent year. Concerns about personnel dosimetry performance date back to the 1950s. Efforts to implement dosimetry performance standards have been attempted several times but were always unsuccessful, primarily because only the performance of the dosimeter and not the dosimetry processor was addressed. The goal of NVLAP remains the satisfactory performance of personnel dosimeters, and of equal import, that of the processor.

**Internal Monitoring**

Because radioactivity is part of the world around us, we take it into our bodies continuously. One way is by inhalation, when radioactive material that is suspended in the air is inhaled into the lungs and then deposited. Radioactive materials become airborne just like dust and dirt. Heating, ventilation, and physical movement serve to increase airborne concentrations in contaminated areas. Another way is by ingestion, when radioactive materials are taken into the mouth and subsequently enter the digestive tract. Ingestion occurs when people eat, smoke, apply cosmetics, or drink in contaminated areas or use contaminated hands. Other ways are through wounds and by direct absorption through the skin. However, absorption is only possible for a very few radionuclides and is dependent on chemical form.

Just as there are regulatory limits on external radiation exposure, there are also limits on the amount of radioactive materials one may take into the body as a result of work as an employee at a site that is licensed by NRC. These limits are known as annual limits on intake. There are basically two industry-standard methods for monitoring intakes of radioactivity. These are the direct bioassay (whole body counting), and the indirect bioassay (excretion analyses).

Whole-body counting is a colloquial term for the measurement of the penetrating radiations emitted from radioactive materials that are contained in the human body, emitted through the body, and detected externally. This bioassay method can be used to determine the amount of radioactivity present in the body at the time of measurement but cannot directly determine the amount that was present at some previous time. That quantity must be inferred from the measured body content of the specific radioactive material, followed by application of mathematical models that describe the behavior of that material in the body.

Indirect bioassay, or excretion analysis, refers to identifying and quantifying radioactive materials that are excreted or removed from the body. Indirect bioassay procedures are used routinely in radiation protection work to monitor personnel for possible accidental intakes of radioactive materials.

After an intake has occurred by inhalation or ingestion, a portion of the radioactive material is absorbed into the bloodstream and deposited in various body organs or tissues or excreted from the body. Therefore, analysis of an individual’s excreta indicates whether an intake has occurred. Examples of excreta that can be used for indirect bioassay include urine; feces; tissue; blood; fingernails; hair; teeth; saliva; sweat; and exhaled breath. However, for most routine internal radiation monitoring programs, urine bioassay, or urinalysis, is the methodology of choice. As time passes and the body begins to excrete radioactive materials retained by various organs, standard indirect bioassay procedures can detect the presence of smaller amounts of radionuclides than is possible by standard whole-body counting techniques. This difference in detection capability becomes even greater when insoluble radioactive materials are involved. The actual procedures are specific for the type and form of radioactivity being used in the workplace. In general, however, one or more samples of urine are collected into a sterile bottle, the bottle is sealed, and the sample is shipped to a laboratory that performs radionuclide analysis. The actual analysis procedure is specific for the radioactivity in question. One common method is to place the sample directly over a radiation detector that is connected to a computer-based analyzer. This simple method is actually quite sensitive and requires no sample preparation other than to measure the total volume of the sample. Other methods generally require the sample to be dissolved into a solution, mixed with certain chemicals, then poured through a device that is designed to extract the radionuclide in question.

**Sources of Exposure from Ionizing Radiation**

A series of reports to advise the U.S. government on health consequences of radiation exposures were authored by the National Research Council’s committees on the Biological Effects of Ionizing Radiation (BEIR). The result of these reports is the analysis of the bulk of ionizing radiation data...
to produce a comprehensive updated review of ionizing radiation health effects. The areas of these committees are divided as follows: heritable genetic effects; cellular radiobiology and carcinogenic mechanisms; radiation carcinogenesis; radiation effects on the fetus; and radiation epidemiology and risk modeling. The radiation values are then used by the NRC and EPA to set guidelines and promulgate radiation safety regulations.

**Natural Background Radiation**

Some radiation received by man is natural in origin and ubiquitous. Terrestrial radiation is emitted by the long-lived radionuclides in rocks and soils (Table 23.12), some of which become incorporated into the human body through the food and water supply. Soils formed from igneous rock contain large amounts of uranium and, therefore, radon. Most soils contain some uranium, making radon omnipresent. EPA estimates that radon contributes two-thirds of the natural dose to the average American. Indoor radon exposure is reducible, and low concentration levels are mandated. This topic is given more consideration later in this chapter.

Cosmic radiation (photons and particles) originates in outer space and contributes to external radiation dose (around 8% of total) especially at high altitudes closer to the propagating sources without the benefit of air attenuation. Internal dose (about 11% of total) results from radionuclides (14C) created in the upper atmosphere distributed by meteorological conditions. Long-lived potassium 40 (40K) contributes to internal dose via food consumption.

In fact, natural radioactivity in the environment is at almost the same level today as it was at the beginning of the Neolithic Age, more than 10,000 years ago. Our bodies harbor measurable amounts (>1×10^9 atoms) of radioactive atoms. About half of the radioactivity in our bodies comes from 40K, a naturally radioactive form of potassium. Potassium is vital and is especially important for the brain and muscles. The remainder of radioactivity exposure is caused by radioactive carbon and hydrogen. There is about 4.4 kBq (120 nCi) of radioactivity in the human body. These naturally occurring radioactive substances expose humans to as much as 250 microSv (25 mrem/year).

Most radioactive substances enter the body as part of food, water, or air. The radioactive as well as the nonradioactive isotopes of essential elements such as iodine and sodium can be found in all foods. In a few areas of the United States, the naturally occurring radioactivity in drinking water can result in a dose of more than 0.01 Sv or 10 mSv (>1000 mrem in 1 year).

In general, the foods we eat contain varying concentrations of radium-226, thorium-232, potassium-40, carbon-14, and hydrogen-3, also known as tritium. Examples include salad oil, 181 Bq/L (4900 pCi/L); milk, 52 Bq/L (1400 pCi/L); whiskey, 44 Bq/L (1200 pCi/L); beer, 14 Bq/L (390 pCi/L); tap water, 1 Bq/L (20 pCi/L); brazil nuts, 0.5 Bq/g (14.00 pCi/g); bananas, 0.1 Bq/g (3.00 pCi/g); flour, 0.01 Bq/g (0.14 pCi/g); and peanuts and peanut butter, 0.004 Bq/g (0.12 pCi/g).

Another type of natural radiation is cosmic radiation given off by the sun and stars in outer space. Because the earth’s atmosphere absorbs some of this radiation, people living at higher altitudes receive a greater dose than those at lower altitudes. In Ohio, for example, the average resident receives a dose of about 400 µSv/year (40 mrem) in 1 year from cosmic radiation. In Colorado it is about 1800 microSv (180 mrem) in 1 year. Generally, for each 100-foot increase in altitude there is an increased dose of 1 mrem per year. Flying in an airplane increases our exposure to cosmic radiation. A coast-to-coast round trip gives us a dose of about 40 microSv (4 mrem). In Ohio, radiation in soil and rocks contributes about 600 microSv (60 mrem) in 1 year to human exposure. In Kerala, India, this radioactivity in soil and rocks can result in an exposure of 40 mrem (0.4 mSv).

<table>
<thead>
<tr>
<th>Series Name</th>
<th>Mass</th>
<th>Initial n</th>
<th>Final n</th>
<th>Initial</th>
<th>T_1/2</th>
<th>Final Stable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorium</td>
<td>4n + 0</td>
<td>58</td>
<td>52</td>
<td>232Th</td>
<td>10^10</td>
<td>206Pb</td>
</tr>
<tr>
<td>Neptunium</td>
<td>4n + 1</td>
<td>60</td>
<td>52</td>
<td>237Np</td>
<td>10^6</td>
<td>209Bi</td>
</tr>
<tr>
<td>Uranium</td>
<td>4n + 2</td>
<td>59</td>
<td>51</td>
<td>238U</td>
<td>10^9</td>
<td>206Pb</td>
</tr>
<tr>
<td>Actinium</td>
<td>4n + 3</td>
<td>58</td>
<td>51</td>
<td>235U</td>
<td>10^9</td>
<td>207Pb</td>
</tr>
<tr>
<td>40K</td>
<td>40Ca</td>
<td>58</td>
<td>51</td>
<td>40Ca</td>
<td>10^9</td>
<td>40Ca</td>
</tr>
<tr>
<td>14C</td>
<td>14N</td>
<td>58</td>
<td>51</td>
<td>14N</td>
<td>10^4</td>
<td>14N</td>
</tr>
</tbody>
</table>

Note: All nuclides with Z ≥ 84 are naturally radioactive; some with Z < 84 are naturally radioactive. In particular, 40K and 14C are important. There are three naturally occurring series of radionuclide. The fourth series, the neptunium series, has a half-life so short that any naturally occurring members of the series have decayed. It can be produced in the laboratory. 

T_1/2 = physical half-life in year

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Table 23.12 — Natural Radioactivity
excess of 30 mSv (3000 mrem) per year, and at a beach in Guarapari, Brazil, radiation levels have been measured in excess of 50 microSv (5 mrem) in a single hour. Some of the residents who use that beach receive doses approaching 10 mSv (1000 mrem) per year. In a wooden house the natural radioactivity in the building materials results in a dose of 300 to 500 microSv (30 to 50 mrem) per year. In a brick house the dose is 500 to 1000 microSv (50 to 100 mrem) per year. And if a home is so tightly sealed that the leakage of outside air into the home is small, natural radioactive gases (radon) can be trapped for a longer period of time and thus increase dose. Typical members of the U.S. population may receive the following types of radiation exposures:

- 1300 mrem per year for the average cigarette smoker
- 650 mrem per nuclear medicine examination of the brain
- 509 mrem per nuclear medicine examination of the thyroid
- 405 mrem per barium enema
- 245 mrem per upper gastrointestinal tract series
- 150 mrem per nuclear medicine examination of the lung
- 110 mrem per computerized tomography of the head and body
- 7.5 mrem per year to spouses of recipients of certain cardiac pacemakers
- 6 mrem per dental X-ray
- 5 mrem per year from foods grown on lands in which phosphate fertilizers are used
- 4 mrem per year from highway and road construction materials
- 2 mrem per year from the use of gas mantles
- 1.5 mrem from each cross-country airline trip (one way)
- 1 to 6 mrem per year from domestic water supplies
- 1 mrem per year from television receivers
- 0.5 mrem from eating one-half pound of brazil nuts
- 0.3 mrem per year from combustible fuels, (i.e., coal, natural gas, and liquefied petroleum)
- 0.2 mrem from drinking a quart of Gatorade® each week
- 0.1 mrem per year from sleeping with one’s spouse (or “significant other”)

These very small but detectable levels of radioactivity are a natural consequence of life itself. We are exposed to a constant stream of radiation from the sun and outer space. Radioactivity resides in the ground, air, buildings, food, water, and products in use. The average person in the United States receives a dose of about 0.0036 Sv/year (360 mrem per year) from these natural sources of radioactivity in addition to typical medical radiation exposures such as X-rays.

No effects have ever been observed at doses below 50 mSv (5000 mrem) delivered over a 1-year period. In fact, effects seen when humans are exposed whole body to 1 Gy (100,000 mrad) over a short period are temporary and reversible. It takes a short-term whole-body dose of well over 5 Gy (500,000 mrad) to cause a fatality.

**Radon**

Radon, a noble gas, is classified as a lung carcinogen in humans, with substantial evidence to support its classification. Exposure to the naturally occurring radionuclide radon and its progeny is regarded as the largest contributor of radiation exposure from natural sources to humans. EPA estimates that 5000–20,000 lung cancers per year are associated with radon exposure in air. The National Academy of Sciences estimates 13,500 deaths per year.

Radon in drinking water poses the risk of stomach cancer from ingested water, based on 1 L per day intake. EPA uses a 10 to 1 transfer coefficient of radon in water to radon in air (10,000 pCi/L of radon in water contributes 1 pCi/L of radon in air) and estimates that about 5% of radon in homes originates in drinking water. Exposure to radon imbibed in drinking water is about 20% of the risk from inhaling the radon.

The origin of the radon (²²⁴Ra) in air and in water derives from the naturally occurring decay chain of ²³⁸U. Each of the intermediate decay products in this chain has a characteristic physical half-life before terminating in the stable nuclide of ²⁰⁶Pb. There are two other isotopes of radon (²¹⁹Rn and ²²⁰Rn) produced in natural soils from two independent natural decay schemes. Because the predominant decay series of the four original nuclides; and terminates at stable ²⁰⁶Pb. Radium in rock, soils, or concrete decays into the noble gas radon with the emission of a 4.78-MeV alpha particle. The recoil momentum can release the radon nucleus from its surroundings and allow it to migrate. Gaseous radon with a half-life of 3.82 days diffuses and evolves from soils, and on decay it begins a solid phase series of radon daughters.

The decay series of ²²²Rn begins with ²³⁸U; emits alpha, beta, and gamma radiation at specific nuclides; and terminates at stable ²⁰⁶Pb. Radium in rock, soils, or concrete decays into the noble gas radon with the emission of a 4.78-MeV alpha particle. The recoil momentum can release the radon nucleus from its surroundings and allow it to migrate. Gaseous radon with a half-life of 3.82 days diffuses and evolves from soils, and on decay it begins a solid phase series of radon daughters.

As a monatomic noble gas, radon is relatively insoluble, and after being inhaled is exhaled rather than absorbed and will not be deposited on surfaces. It emits alpha radiation of high energy, which, if it decays during residence in the lung, produces damage and radioactive daughter products. Radon becomes a biological hazard when it remains long enough in the lung to decay into its daughter products. It is the progeny of radon, not
To the first four decay products of 222Rn: 218Po, 214Pb, 214Bi, and 214Po. These four radon progeny have short enough half-lives to decay in the lung before being physiologically removed and are responsible for the radiation dose delivered to the lung. The target cell in the lung from radon exposure is the bronchial epithelium, which is the site of the majority of lung cancers considered to be caused by radon. The fifth decay step is 206Pb, which has a long enough half-life (22.3 years) to be removed from the lung by physiological processes before it decays.

The radon concentration in air over typical soil depends on meteorological conditions. When confined to a defined volume, the radon progeny decay by secular equilibrium to 210Pb in approximately 4 hours. The equilibrium fraction is the fraction of decaying daughters divided by the number of radon atoms. A fraction of 1 is the value when the number of decay products from progeny equals the number of decay products from the 226Ra. If a fraction of the radon is removed from the defined volume, the fraction of progeny decreases. The values of radon progeny outdoors are at about 70% of the equilibrium value. EPA estimates that the average outdoor concentrations are 8 Bq/m³ or 200 pCi/L or 0.001 WL (working level) for someone working outdoors continuously.

The WL (/m³) represents a derived standard based on human epidemiological studies of working miners to relate the risk from radon exposure to the incidence of lung cancer.27 The working level month (WLM) is defined in terms of energy deposition over a working month. The dose equivalent unit of the Sievert is not used.

The progeny of radon are solid phase, ionized nuclei, that have a high likelihood of becoming electrostatically attached to aerosols. Because they are ionized, progeny can attach to an aerosol or remain unattached. Progeny have a characteristic high surface area-to-volume ratio with a geometric diameter range between 0.001–100 mm. Neutral particles adsorb on aerosols. Then, when inhaled, the aerosols with radon deposit on the interior surfaces of the lung. The aerosol factors include the size distribution of the particle, the fraction unattached, and the equilibrium factor. Outdoors, the unattached fraction is below 10%. Unattached fractions consist of free ions, micrometer-size agglomerates with water molecules, which plate out with about 100% efficiency in the lung. Thus, the dose (per WLM) from one unit of an unattached fraction will be greater than the dose (per WLM) from the same unit of an attached fraction.

Radon progeny preferentially attach to aerosol particles. The calculation of the radiation dose becomes complex when the radon becomes attached to particles with different solubilities and particle size. This distribution of the fraction of the attached/unattached groups is critical to dose evaluation because the dose is proportional to the unattached fraction. For example, nasal breathing influences more unattached radon deposition, which is cleared from the nasal passages on exhale. Particle size attachment determines in which part of the airway the radon will be deposited. Radiation dose to the bronchial epithelium depends on the amount of radon, the aerosol mixture, and the physiology of the lung.

When confined to a constant volume, radon remains in equilibrium with its progeny. Measurement of radon in air requires knowing or estimating the equilibrium constant. When radon is subject to air convection currents or ventilation, the equilibrium value is reduced from a value of 1 for equilibrium conditions. When trapped indoors, the fraction of radon in equilibrium with its progeny depends on the ventilation rate for the structure. The equilibrium fraction used by BEIR IV and the International Commission on Radiological Protection (ICRP) for the risk evaluation from radon exposure is 0.5 for existing housing and is the fraction required for EPA evaluation. The rationale of radon mitigation is that the equilibrium fraction is disrupted and reduced in value to 0.5 by venting the radon to an outside air space, where the decay process continues away from the living space. Measurement of radon in air in a dwelling is predicated on a constant 0.5 fraction and is defined as “closed house conditions.”

It may be prudent for the industrial hygienist to evaluate potentially elevated radon concentrations or reevaluate existing mitigation conditions. Radon in water and radon in air in the home and public buildings in excess of a mandated level are required to be mitigated. See Tables 23.13 and 23.14. The mandates govern public water systems, which are defined as having 15 or more service connections or regularly serving at least 25 persons for 60 or more days per year. Normally, a public water supply does not have elevated levels of radon but may have other regulated radionuclides.

### Table 23.13 — EPA Action Levels for Indoor Radon in Air

<table>
<thead>
<tr>
<th>Concentration (pCi/L)</th>
<th>EPA Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.25</td>
<td>not practical; considered de minimis</td>
</tr>
<tr>
<td>1-4</td>
<td>recommend reduction</td>
</tr>
<tr>
<td>4 (0.02 WL)</td>
<td>action level as annual average</td>
</tr>
<tr>
<td>4-20</td>
<td>action required within year</td>
</tr>
<tr>
<td>20-200</td>
<td>action required within months</td>
</tr>
<tr>
<td>&gt;200</td>
<td>action required weeks</td>
</tr>
</tbody>
</table>

**Note:** Outdoor radon standards are limited to uranium and phosphorus mine vents. (For more information, see www.epa.gov)
Radon mitigation regulations cover indoor air and drinking water but do not account for the environmental fate of the radon in outdoor air. The U.S. Geological Survey and EPA developed the Map of Radon Zones to pinpoint communities of high radon concentration.

**Artificial and Technologically Enhanced Radiation Exposure**

Human activity raises radiation exposure due to discharges from coal fired ($^{14}$C) and nuclear plants (a large spectrum of short-lived radionuclides and low levels of long-lived radionuclides). Radioactive discharges from nuclear power plants are limited to specific discharge levels above environmental background. Radiocarbon and ash from the coal fired plants are not regulated. Population exposure from operation of a 1000-MW coal fired plant is 100 times that for a nuclear plant at 4.9 person-Sv/year (490 person-rem/year compared with 4.8) and releases 5.2 tons of uranium and 12.8 tons of thorium to the atmosphere each year. Air from underground uranium mines and phosphorous plants contain $^{222}$Rn and are regulated to maximum concentration effluent limits.

Artificial radiation exposure for the average American may or may not be regulated. Medical facilities can discharge low-level, nonbiologically contaminated medical radionuclides into the sewer system. Patient excreta with radionuclides is exempt from regulation. Medical exposures are not regulated, and the largest radiation from medical causes is due to diagnostic X-rays, including dental X-rays, that contribute about 11% of the total annual dose to the average American. Any licensed practicing professional (e.g., physician, chiropractor, dentist) using diagnostic X-rays, photons for therapy, or radiopharmaceuticals can prescribe what is considered state-of-the-art doses to deliver the level of care required for the specific instance. Radiation protection occurs by limiting duplicate procedures.

**Consumer Products**

There are many examples of radiation and radioactivity in products commonly used by the public. Examples include electronically generated radiation, radioactivity in consumer products, and radionuclides intentionally added to the product. Examples of each type of radiation are provided in following paragraphs, including the nature of the product, the radioactivity concentrations, and/or radiation levels likely to be present.

**Electronically Generated Radiation**

The best and most widely used example of a consumer product that produces radiation through electronic means is the tried-and-true television set. Other examples are video display terminals (VDTs), airport inspection systems, and obsolete shoe-fitting fluoroscopes. The type of radiation associated with these devices is X-ray, a type of photon radiation produced when high-energy electrons impact a stationary object, such as the television picture tube or a computer monitor. The X-rays are not necessary for the operation of a television set, and this is just one example in which the radiation is a byproduct, meaning it is incidental or extraneous to the purpose for which the consumer product was originally designed. The operating voltage is the primary factor. As the voltage is increased, the X-ray intensity increases. To counter this, the use of thick walls in picture tubes can reduce the X-ray emissions. The highest X-ray emission levels recorded were produced in two particular years, 1968 and 1969.
Radioactivity in Consumer Products

Tobacco contains naturally occurring radioactive materials. Because tobacco is a crop grown in the soil, it will chemically bioaccumulate atoms of naturally occurring uranium and thorium series as well as potassium-40 ($^{40}$K), a ubiquitous naturally occurring beta-gamma emitter with a long half-life (<$^{10}$ year). Of greatest importance from a radiological perspective, tobacco contains polonium-210 ($^{210}$Po) and lead-210 ($^{210}$Pb)—radioactive progeny (daughter products) produced in the uranium series. The presence of these radionuclides can be explained by at least plausible reasons. First, $^{210}$Po and $^{210}$Pb are radionuclides present on tobacco leaves from the deposition and subsequent decay of airborne progeny of radon-222 ($^{222}$Rn). Second, the tobacco plant also has a preference for concentrating lead found in the soil. Third, phosphate fertilizers, routinely used in tobacco fields, contain measurable concentrations of $^{210}$Pb and $^{210}$Po (from the decay of uranium found in the phosphate). The effects of tobacco on human health and the link to lung cancer is widely cited and discussed, but that is not the focus of this discussion. It has been estimated that the amount of $^{210}$Pb and $^{210}$Po residing in the lungs and bones of U.S. smokers is approximately four times and two times that of nonsmokers, respectively. Lastly, the additional annual dose equivalent to a particular region of the lung—the bronchial epithelium—from smoking the daily average consumption of 30 cigarettes is approximately 0.15 Sv (15,000 mrem). Radioactivity is commonly found in building materials, with radionuclides of uranium, thorium, and potassium. Radiation exposures are not excessive, especially when compared with the annual natural background. Dose estimates place the average annual whole-body external dose at 70-100 microSv (7 to 11 mrem) from homes of masonry and concrete construction. Houses are constructed on soil that also contains naturally occurring materials. Decay of uranium and thorium results in the formation of gaseous radon and daughter progeny, which contributes to lung dose. In addition, naturally occurring radioactive materials can appear in well water used inside a home as a domestic water supply. Internal exposure is of greater importance, especially in poorly ventilated or tightly enclosed homes. For this reason, EPA has advocated for several years that homeowners evaluate their homes for the presence of airborne radon gas.

There are many examples of naturally occurring radioactive materials present in consumer products beyond those already discussed. These include highway and road construction materials, mining and agricultural products (e.g., fertilizers and other phosphate products), and combustible fuels (coal, oil, natural gas, etc.). Optical lenses (eyeglasses, etc.) are noted for their thorium content (and consequently may contain elevated levels of thorium) because this element often appears as an impurity in the rare earth oxides used to produce certain types of glass.

This category contains several items, including, but not limited to, smoke detectors, radioluminescent products, static eliminators, uranium glazes and ceramics, dental fixtures, gas lantern mantles, ophthalmic glass, and welding rods. Smoke detectors are one of the most common consumer products. Used to signal the presence of smoke/fire, these detectors typically contain an Americium-241 source with a small amount of radioactivity, on the order of 37 kBq (1 µCi). When smoke particles enter the detector, they disrupt the flow of current (electrons) created by the ionization of alpha particles produced from the decay of the americium. This disruption triggers an alarm. For this reason, they are known as “ionization-type” smoke detectors. The radiation levels emitted from these devices cannot be distinguished from background levels. To further make a point, it has been estimated that the annual average dose equivalent to the U.S. population from these devices is less than 0.08 microSv (<0.008 mrem), far below the annual natural background in the United States.

Radioluminescent products include radionuclides almost exclusively limited to $^{220}$Ra, promethium-147 ($^{147}$Pm), and tritium (H-3). $^{220}$Ra is an alpha/beta/gamma emitter with a half-life of 1600 years. $^{147}$Pm is a beta emitter with a half-life...
of 2.6 years. Tritium, a radioactive isotope of hydrogen, has a relatively short half-life of 12.3 years. Zinc sulfide (ZnS) is the most commonly used scintillating material for radioluminescent products. The products are simple devices. The radionuclide and the scintillator are mixed together and then plated in some kind of container, such as a glass tube. The radionuclide decays and emits a particular type of radiation. For example, $^{226}$Ra is primarily an alpha emitter; $^{147}$Pm and $^3$H are beta emitters. When either of these radiations interacts with the ZnS, a small flash of light is produced. This type of product is typically found in watches and clocks. $^{226}$Ra, $^{147}$Pm, and $^3$H all have been used in combination with (primarily) ZnS, though the vast majority of these devices today use the beta emitters $^{147}$Pm and $^3$H. Watches and clocks employing $^{226}$Ra have not been produced in the United States since 1968 and 1978, respectively, although there are a number of these antiques still available. In the United States the NRC requires the manufacturer to obtain a radioactive materials license for watches/clocks containing either $^{147}$Pm or $^3$H. NRC also limits the amount of radioactivity that may be present in an individual timepiece. For $^{147}$Pm there is an additional limitation on the permissible dose rate. Health concerns have been reduced by eliminating the use of radium and using the weak beta emissions of the shorter half-life $^3$H and the less hazardous $^{147}$Pm.

Timepieces containing $^3$H have been known to leak occasionally, resulting in a small whole-body dose from inhalation or absorption through the skin and contamination of clothing, surfaces, and so forth. There is no particular concern with $^{147}$Pm, although specific dose rate limits are cited for this radionuclide at a stated distance (e.g., 1 cm, 10 cm) from the timepiece depending on its type (i.e., wrist watch, pocket watch, clock). For both $^3$H and $^{147}$Pm the estimated annual dose equivalent to an individual user is much less than 10 microSv (1 mrem).

$^3$H also is used in a variety of applications. Aside from timepieces these include self-luminous aircraft and commercial exit signs, luminous dials and gauges, and the production of luminous paints. Care must be taken with its production and use because the weak beta emission energy—18 kiloelectron volts (18 keV) maximum, about 6 keV average—is essentially impossible to detect with conventional survey instruments. Therefore, if a leak occurs, for example, in a production facility, an entire facility can become contaminated and the problem potentially not discovered for some time unless specialty instruments are used for routine surveillance. This situation has occurred (though fortunately, rarely). More important, however, is that in the last few years there have been instances when $^3$H exit signs have been stolen. These devices are “generally licensed” by NRC and may contain up to 925 GBq (25 Ci) of $^3$H.

Static eliminators have been used for a number of years in industrial settings to reduce electrical charge buildup in various materials. In a more general application in the United States, $^{210}$Po, an alpha emitter produced eventually from the decay of uranium-238 ($^{238}$U), is incorporated into so-called static eliminators to reduce/eliminate the static charge produced during the manufacture and use of photographic film and phonograph records. Regarding the latter, those individuals familiar with phonograph records (before the advent of CDs, DVDs, etc.) may well have used a $^{210}$Po bearing static eliminator to reduce the amount of dust attracted to the static charge on the record surface. In brief, ionizations from the polonium alpha particles neutralize the charge on the dust particles, reducing their accumulation on the surface being cleaned.

Uranium is commonly found in colored glazes. It was used in various chemical forms as far back as the 1920s to produce glaze colors of black, brown, green, and much of the spectrum from yellow to red. Beginning in the 1930s orange was quite popular in the production of a particular line of dinnerware known as Fiesta®. Although the current manufacturer no longer uses uranium in its manufacturing process, these dinner services can be found in flea markets and in many homes. Emissions of primarily beta and gamma radiation can be detected. Even though alpha particles are emitted during the decay of uranium, these radiations are absorbed and contained by the glaze. The radiation emanating from Fiesta® dinnerware is readily apparent using any basic radiation detection device such as a Geiger counter. External surface dose rates range from 5–200 µGy (0.5 to 20 mrad/hour), with an average dose rate from a complete Fiesta setting being about 30 µGy (3 mrad/hour) at a distance of 1 inch, the approximate distance to the hands. The dose rate to the whole body would be 10 or more times lower.

Thorium products also are encountered in the use of welding rods. In the 1970s thorium was added to eyeglasses to produce a pink tint. Another application involved its incorporation into very high-quality lenses to improve the transmission of light. This characteristic has been used by the military in their night sights, for example. It also has been used in older 35-mm Pentax™ cameras and television cameras. The limits appear in NRC regulation (10 CFR 40.13). For contact lenses, eyeglasses, binoculars, and other items in close contact with the eye, this regulation places a limit of 0.05% by weight of thorium. For lenses that are not designed for eye contact, limits up to 30% by weight are permitted. Older lenses still in use could result in nontrivial doses to the outer (germinal epithelial) layer of the cornea. For example, eyeglasses containing the maximum (0.05%) thorium limit could result in an annual dose of 40 mSv/year (4000 mrem/year) to this...
area. Because of this potential exposure, direct exposure of the eye to lenses at a close distance for extended periods of time should be avoided. There also have been isolated cases reported in which higher than permitted thorium quantities (greater than 0.05% by weight) were added to eye-pieces without proper marking/labeling signifying the addition of thoriated glass.

Thorium can be found in welding rods containing tungsten (“thoriated tungsten”) to produce easier starting, greater arc stability, and less weld metal contamination. According to NCRP, about 300,000 people work either directly or indirectly with thorium-bearing welding rods. Doses from welding rods result through their distribution, use, and disposal. However, actually using the devices is the primary source of exposure. Welding rods contribute both an external whole-body dose and an internal (inhalation) dose from radon-222 and its progeny. The latter pathway predominates. Although doses from external exposures are estimated to be less than 10 microSv per year (1 mrem/year), the whole-body and bone dose commitments from internal exposures vary widely depending on relative use (“heavy,” “occasional,” personnel assisting the welder, etc.). The highest whole-body and bone dose estimates are 140 microSv (14 mrem) and 20,000 microSv (2,000 mrem), respectively.

**Industrial Uses**

There are widespread uses of radiation and radioactivity in industrial operations. Current manufacturers and researchers take advantage of the following four characteristics of radiation sources for industrial uses: radiation affects materials; materials affect radiation exposure; radiation traces materials; and radiation produces heat and power in a variety of industries. Applications such as pasteurization and sterilization of food, polymerization of organic compounds, sterilization of medical supplies, and elimination of static polymerization of organic compounds, sterilization; use, and disposal. However, actually using the devices is the primary source of exposure. Welding rods contribute both an external whole-body dose and an internal (inhalation) dose from radon-222 and its progeny. The latter pathway predominates. Although doses from external exposures are estimated to be less than 10 microSv per year (1 mrem/year), the whole-body and bone dose commitments from internal exposures vary widely depending on relative use (“heavy,” “occasional,” personnel assisting the welder, etc.). The highest whole-body and bone dose estimates are 140 microSv (14 mrem) and 20,000 microSv (2,000 mrem), respectively.

Likewise, the intensity of nuclear radiation is reduced by thicker or denser materials that are in the path of the radiation. This is the characteristic that is responsible for such applications as radiographs.

In metals industries where blast furnace operations are used, radioactivity is used to study the residence time and distribution of constituents in the various metallurgical processes. Other tracer studies compare methods of chemically cleaning copper and stainless steel parts, evaluating plating techniques, and adding to our knowledge of the structure of electroplated coatings. Radionuclides also have been used to evaluate the diffusion of gases into metals (causing brittleness), and they have been used to provide valuable information on the rate of tool wear.

Using radioactivity to gauge thickness has been well recognized by industry. Radiation permits continuous control of the uniformity of the thickness of various kinds of sheets and layers to very close tolerances. Furthermore, these types of systems can be completely automated so that the response to thickness changes can be used to actuate rollers, thus providing closer control than would otherwise be possible. But in addition to thickness, radioactivity can be used to measure the density of various materials. The density of liquid slurries, powders, and granular solids can be measured by having a radiation source and a detector mounted on opposite sides of the material being measured (i.e., like in a hopper or pipeline). If the detected intensity of radiation from the source increases or decreases, the density of the material has decreased or increased, respectively.

The major advantages of radiography using a radiation source versus an X-ray machine for an inspection are portability, the absence of electrical wires and connectors, and the ability to make exposures with the source of radiation placed inside a complex shape. The use of radioactive cobalt-60 for flaw detection in masses of metal was one of the earliest applications of radionuclide radiography. Most foundry operations maintain a selection of radiation sources, including radioactive cobalt, iridium, and cesium. Although X-ray machines are still used, radiation sources are the preferred methodology when the shape and accessibility of the casting makes X-ray techniques less effective. Although the purchase price of a radioactivity-bearing device can be much less than the price of an X-ray machine, compliance costs for users of radioactivity tend to be much higher than for users of radiation-producing machines.

There are uses for radiation in the electrical industry also. One example is the use of radioactive krypton gas for leak testing. This procedure involves exposing electronic components to the gas under pressure, during which any leaky components are at least partially filled with the gas. After the exposure period the surfaces of the components are cleaned, and the leaky components are quickly identified by detecting the residual radioactivity. For example, the procedure is used to study adsorption and desorption of mercury by glass surfaces in mercury switches. In addition, there are studies of corrosion of silver contacts by fused salt; the development of high-integrity compression seals; evaluation of methods for cleaning metal surfaces prior to electroplating or enameling; wear testing of bearings; determination of lubrication and seal characteristics; and improving the doping of semiconductors by investigating the mechanisms of the diffusion. Radiation sources also are used for static elimination, in fire detection equipment, and in luminous dials, gauges, and signs. Certain navigational lights also contain radioactivity. In addition, there has been considerable interest in the use of radionuclides to replace batteries and related power sources.
The use of radionuclides in this industry is widespread and includes many different categories. In fact, petroleum refiners were among the first industrial operations to use radionuclides. Refineries pump large amounts of fluids, including raw materials and other in-plant inventory and products. Radiation sources are used as part of the automatic (computerized) control of the flow of these fluids. However, by far the most extensive use of radionuclides in this and other chemical industries is their use as tracers. For example, radioactive sulfur can be used to determine the efficiency of separation; radioactive gold and iodine can be used to determine the thoroughness of mixing; radioactive sodium and bromine are used for locating leaks; and radioactive cobalt and cesium are used for gauging liquid or solid levels. Other radiation sources might be used to study process stream flow patterns; locate pipe obstructions; study mass balances in refinery streams; measure flow velocities; study catalyst movement; study carbon deposits in fuel research for drug metabolism studies; determine tire wear; study diffusion in glass; eliminate static; and sterilize medical supplies.

There are many applications for radioactivity in consumer product industries. Trace amounts of radioactivity (106Ru or 106Rh) are sometimes used for determining the rate of wear in floor wax. It also can be used to assess laundering efficiencies of various detergents. Radioactivity has been used to determine the firmness of cigarettes; the rate of pesticide removal from surfaces; the metabolism of food additives; biosynthesis; the movement of textile layers; the control of solid and liquid levels of foods and beverages in their containers; sterilization and pasteurization of food; and even the migration of dyes in the printing business.

**Nuclear Reactors**

A nuclear reactor operates on the physical principle that uranium fissions easily with the addition of a thermal neutron. With the absorption of the neutron, the uranium atom disintegrates into two fission nuclei, gamma, and (on the average) two free neutrons. A nucleus is said to be fissile if absorption of a thermal neutron causes a split into two nuclei. Fissile material contained in a fuel rod is covered with cladding to contain the uranium fission byproducts and transfer heat. Control rods such as boron or cadmium made of low-Z material with a high cross-section for neutrons reduce the kinetic energy of free neutrons for a capture and control of subsequent fission.

Most reactors are intended for electric power generation; there are a few for research. Any reactor can be used as a source of neutrons for research. A pure nonradioactive material is lowered through a specialized port into the reactor pool for exposure to free neutrons. After neutron capture a radioactive isotope of a previously stable element, rich in excess neutrons, is produced. The disadvantage of neutron activation is that the contained product is a mixture of radioactive and nonradioactive isotopes, yielding a relatively low specific activity product. The time of irradiation can be lengthened to increase specific activity, but the radioactive component decays, prohibiting the practicality of the use of very short-lived radionuclides.

After the uranium fuel rod is spent and no longer of use in the reactor, the fission products can be chemically separated from one another, yielding radioactive products that have high specific activity. The disadvantage of this process over neutron activation is that the product can be contaminated with materials of similar chemical properties. Radionuclides with excess neutrons decay by the beta/gamma process. Radionuclides that are produced from neutron activation or from fission byproducts are licensed by NRC or an agreement state.

**X-Ray Machines**

A conventional X-ray machine accelerates electrons in the keV energy range. The X-ray tube is an evacuated tube that accelerates electrons to a maximum voltage and controls the maximum energy of the X-ray, which is the stated value of the spectrum. When the electrons are rapidly slowed down, X-rays are produced by the conversion of kinetic energy to electromagnetic energy. The majority of X-rays produced are emitted from a target at a back angle. Most of the X-rays produced in X-ray machines produce a spectrum of a continuous distribution of photons from a minimum energy determined by filtration to the peak voltage energy. The energy produced is stated in terms of kVp, the “p” referring to peak voltage set on the controls. The bremsstrahlung curve is called the continuous X-ray distribution curve. The window of an X-ray machine is made with low-Z material to allow penetration of the lower energy X-rays. Application of medical X-ray machines can be dental or radiographic X-ray or some therapy. The average energy of an X-ray spectrum is determined by a process called the half value layer. An output radiation rate for each machine is specified with the peak voltage value and the half value layer. All dental, diagnostic radiology, and some superficial radiation therapy machines fall into this group. Research X-ray machines in this range require personnel protection, particularly for the hands and eyes.

X-ray machines for medical use fall into special categories, and their operation and compliance requirements are within state jurisdiction. Radiopharmaceuticals for medical and veterinary purposes fall under jurisdiction of NRC. Current applications of such machines are listed in Table 23.15.
the cell within a very short time, defined as a double strand break, the event is usually lethal to the direct effect of ionizing radiation on cells causes a major discontinuity in the primary structure. If a strand break or a double strand break, causing a disruption of the DNA strand, either a single or a double hit is one in which the interaction from the DNA to cause the lesion. The amino acid bases of the DNA display a relative radio sensitivity: thymine (most sensitivity), cytosine, adenine, and guanine (least sensitive). The lesions may or may not end in the death of the cell but may produce altered cellular metabolism.

The majority of surviving cells from a radiation interaction can be injured with sublethal damage caused by an indirect hit. Low LET and low RBE radiation and high-energy beta rays are not efficient in the production of double strand breaks and usually produce single strand breaks. The intermediaries of the free radicals in the cell cause the majority of DNA damage. This damage is not usually lethal to the cell because some of it is sufficiently repaired. However, repair mechanisms themselves are subject to misrepair, and the cell line is altered with repeated injury.

In the nomenclature of toxicology, the terms direct and indirect as applied to the effects of chemicals on DNA have different definitions from those used in radiation physics. The direct effect in toxicology means that the DNA has a chemical additive, an adduct, attached to the DNA. That attachment is the putative cause of disruption of biological effectiveness; see Table 23.2) ionizing radiation, such as alpha and low-energy beta particles, tend to cause more direct hit deaths; however, the few survivors from this type of radiation induce more chromosomal aberrations than the more plentiful survivors from low LET damage. Sublethal damage caused by high LET radiation is not repaired to the same extent as that from exposure to low LET radiation.

Indirect hits result most likely from interaction with a water molecule rather than DNA, which then releases a free radical or radicals. Damage from the indirect effect requires more time to manifest the effects of cell damage. Cell content is mostly water, so the majority of free radicals are free water radicals. Indirect interaction can cause multiple effects, one of which is chromosome damage. The free radical then interacts with the DNA to cause the lesion. The amino acid bases of irradiated DNA display a relative radio sensitivity: thymine (most sensitivity), cytosine, adenine, and guanine (least sensitive). The lesions may or may not end in the death of the cell but may produce altered cellular metabolism.

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The indirect chemical effect, an epigenetic effect, requires chemical modification by a metabolic process to initiate the damage process. The activated form of the molecule is then the putative cause of a change in the DNA and lesions that can cause cancer or terata (birth defects).

Membrane integrity is required for normal cell metabolism. Damage to the cell membrane is considered one of the major factors causing cell death. Membranes can be degraded in one of two ways, either by activation of membrane phospholipases in an ischemic condition or by free radical attack. Free radicals are generated in normal cell metabolism, and all free radical formation is highly lipophilic, causing damage to the cell membrane. In particular, unsaturated lipids are susceptible to peroxidation by ionizing radiation. Radiation injury, like chemical and ultraviolet radiation exposure to membranes, increases cell free-radical formation and cellular damage.

Exogenous chemicals can enhance or diminish cellular damage. Certain chemicals in cigarette smoke, for instance, are highly associated with lung cancer. In uranium mine worker epidemiological studies, the nature of the dust is important in the evaluation of lung cancer risk. If the factors influencing membrane composition are altered, as with chemical application or excessive cell regeneration (hyperplasia), the sensitivity to radiation can be modified, increased, or even decreased.

In summary, ionizing radiation particles in comparison with photons have higher LET and tend to kill the cells directly with double strand DNA breaks. There are relatively few survivors to this damage, but those that survive tend to have greater chromosomal damage even after repair. Low-energy photons with low RBE and low LET tend to kill and injure the cells indirectly by free radical attack and cause single strand DNA breaks. This type of damage occurs more frequently and can possibly be handled by cell repair mechanisms at lower dose rates.

### Dose Response Curve

The dose response curve is a mathematical relationship between the severity of the radiation effect and the total dose (see Figure 23.2). Dose response curves are used to characterize living systems. The respondents can be individual cells in a cell line or a complete animal such as the standard test animals used by the National Toxicology Program. Even with the standard rabbit or laboratory inbred rat lines, individual variation to a toxin necessitates the establishment of a response curve under controlled conditions to represent the median response. Epidemiology studies are used to estimate the dose response of humans.

In 1949 the ICRP formulated the first “standard man,” a human model to specify the masses of important critical organs and tissue to be used for radiation dose evaluation. Refinement of the model in 1959 included distribution of the elements in the total body, effective radii of organs, and intake and excretion rates. The ICRP model is now called Reference Man and describes an occupational radiation worker who is a 70-kg, 1.7 m tall, 20–30 year old Caucasian male, who lives and therefore breathes in a temperate climate of 10–20ºC and has Western European or North American habits.

The value of the dose at the median response is the LD$_{50}$ (lethal dose to 50% of the population). Human population radiation doses are expressed as LD$_{50}$/30 indicating death to 50% of the population within 30 days. The overall shape of this curve is sigmoid. Deviations from the characteristic shape can provide information about hypothesized mechanisms. The slope of the linear portion from ionizing dose depends heavily on the dose rate. Investigation of the low dose portion of the curve and its mathematical approach to the x-axis can yield information on the occurrence of a threshold response. ICRP adopted a univariate logistic regression linear nonthreshold model for radiation protection in 1977 based on the consensus of the scientific community. Now the existence for the possibility of a threshold is being debated.

In radiation studies, radiation dose rate is one of the most important variables that must remain constant throughout the experiment. For low LET radiation the linear quadratic model for the dose response curve governs the shape. A reduction in the dose rate reduces the quadratic coefficient, which changes the slope of the linear portion of the curve. If the slope rises too rapidly, a small error in the dose delivered will be reflected in a large change in cell death. Relatively high dose rates introduce a much higher rate of double strand breaks.
strand breaks. Likewise, a shallow slope will be displayed with a large change in dose with a relatively small change in cell death, typically found at low dose rates. Ideally, to find the LD₃₇ with accuracy, the slope should be of the linear portion of the curve around the value of 1 [(LD₆₃* - LD₃₇)/(LD₆₃ - LD₃₇) approximately equals 1]. The LD₃₇ is also labeled the 1/e value for radiobiological work; LD₃₇ is defined as 1-D₃₇, and both represent the outer points for the linear portion of the dose response curve.

At low LET there is a finite probability that the radiation will not interact within the two strands separating the critical biological target, the DNA. Strands are separated at about 3 nm. Radiation can cause single or double strand breaks, the double strand break being more serious. At a high spatial rate of energy deposition (high LET) the probability of interaction between the radiation and the DNA increases and approaches 1. The DNA is highly likely to receive a double strand break from the high LET radiation. The frequency of double strand breaks is associated with chromosomal aberrations. Somatic chromosome abnormalities are found at a low rate in the general population but are omnipresent in cancer cells.

**Linear No Threshold Theory (LNT)**

The underlying basis for the LNT hypothesis is the worthwhile objective of controlling radiation doses in humans. The hypothesis states that scientists have observed a linear relationship between radiation dose and effect at high doses. Exposure to naturally occurring radiation eliminates a truly radiation free environment to test the linear relationship at low doses (assumed to be less than 200 mSv or less than 20,000 rem). Consequently, it is assumed for radiation protection purposes that the relationship is indeed linear at low doses as well. This leads to the obvious conclusion that any dose, no matter how small, may be capable of causing some biological damage or detriment. Nonetheless, it has been considered for the past 40 years or so to adopt the philosophy that radiation exposure is harmful at any level. There is no tested scientific evidence to support the assumption that irreparable biological damage occurs at low doses. Therefore, it must remain a theoretical concept. Some professionals refer to the LNT as a theory rather than a hypothesis. In this discussion the two proposed ideas are used interchangeably to avoid the subtle distinctions between these two phrases.

The LNT hypothesis has been adopted by every national and international body that offers radiation protection recommendations or interprets scientific data. These include, but are not limited to, the NCRP, ICRP, the National Academy of Sciences BEIR Committees, the International Atomic Energy Agency, and the United Nations Scientific Committee on the Effects of Atomic Radiation. In addition, the Health Physics Society, in their 2000 position statement, *Safety Standards for the General Public*, endorses the ALARA philosophy (i.e., that there is no absolutely safe dose threshold) as a reasonable basis for radiation protection programs.²

These publications are recommendations by committees and organizations that were established to offer standards and guidance in the areas of radiation safety and dose control. However, regulatory agencies almost always adopt the recommendations of these organizations, in one form or another. For example, in the United States, federal and state regulatory agencies overseeing the safe use of radiation and radioactivity require the application of the ALARA principle, with its LNT basis, in licensee or contractor radiation protection programs.

Natural background doses vary greatly over the world. However, even for populations in which background levels are much higher than those typical of the United States, and even much higher than radiation doses typical of occupational radiation work, no ill effects have ever been observed in the survivors. If the LNT theory were true in these dose ranges, there should be an increased incidence of radiation-related health effects. However, this increase has not been observed. The philosophy “no dose, no matter how small, has some risk associated with it” is conservative and cannot be defended. In the case of natural background there are certain areas of the world where levels of natural radioactivity are quite high relative to what we encounter here in the United States. Particular examples include Ramsar, Iran, and the Kerala region in India. Even so, no adverse health effects of natural radiation have been found in either of these regions (or any other areas of elevated background for that matter). In the workplace setting no evidence of detriment to the workers occupationally exposed to radiation within the established regulatory limits has been shown.

Unlike other areas of study, such as health risks from exposure to air pollutants, in which there is a great deal of direct data in the region of interest, radiation effects have been extrapolated far below the region where any meaningful data exist. This has generated no end of controversy in the radiation safety community regarding its continued applicability. Because it has not been proven, use of the LNT hypothesis requires that latent cancer fatalities be projected from accumulated exposures to very small levels of ionizing radiation. And because they are nothing more than projections, there is no assurance of their validity. In the case of cancer, quantitative estimates of “risk” are reported as the number of cancers per unit dose (e.g., sievert or rem). If the LNT hypothesis is incorporated into the development of risk factors, the risk factors are assumed to be valid for all doses and dose rates, even those approaching zero.
These risk factors arise from epidemiological data from the atomic bomb blasts of Hiroshima and Nagasaki. The argument can be made that these risk estimates are not relevant to “normal” radiological protection situations, when individuals are irradiated with very low doses (on the order of 1 mSv (100 mrem) delivered over an extended period (i.e., 1 year). In Japan, for example, a certain proportion of the population was irradiated “acutely,” that is, in a fraction of a second or a few seconds with near lethal doses as high as 5 Sv (500,000 mrem). These dose rates were orders of magnitude higher than those commonly encountered in radiological protection. Extrapolating over such a vast dose-rate span is certainly grounds for arguing the scientific merits of the LNT assumption. Keep in mind that the LNT hypothesis states that even the lowest, close to zero, radiation dose is detrimental, and can produce a cancer or a hereditary effect. However, no hereditary effects have been discovered in the progeny of survivors of Hiroshima and Nagasaki. The argument can be made that this process. In actuality, a cell may have to divide millions of times before a cancer is formed. If true, predicting cancer as an “outcome” of radiation exposure is impossible in light of the present state of knowledge. This conclusion presents a clear lack of credibility and scientific basis for the LNT hypothesis.

Within error bars, the LNT has merit. However, adoption of the LNT hypothesis as the basis for radiation protection regulations means that significant sums of money are spent in the United States and in other countries around the world to remediate or clean-up residual radioactivity in soils, in buildings, on equipment, and in potentially useful feed materials, even though there is no demonstrable health effect associated with the use of those materials. There are certainly grounds for contesting these expenditures.

Applicable Regulations

Agencies

NRC is an independent agency established by the U.S. Congress under the Energy Reorganization Act of 1974 to ensure adequate protection of the public health and safety, the common defense and security, and the environment in the use of radioactive materials in the United States. Licensing and related regulatory functions were transferred to NRC. The agency’s scope of responsibility includes regulation of commercial nuclear power reactors; non-power research, test, and training reactors fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste. Through a comprehensive inspection and enforcement program, NRC ensures that the facilities operate in compliance with strict safety standards. NRC consists of five commissioners; the chairman is appointed by the U.S. president. Each commissioner must be confirmed by the U.S. Senate.

The licensing and regulation of radionuclides in the United States are shared by NRC, EPA, and many state governments. EPA is also responsible for, among other things, setting air emission and drinking water standards for radionuclides. The states regulate radioactive substances that occur naturally or are produced by machines, such as linear accelerators or cyclotrons. FDA regulates the manufacture and use of linear accelerators; the states regulate their operation.

Regulations established by NRC are published in the Federal Register and become incorporated into the Code of Federal Regulations. In addition to regulations, NRC publishes regulatory guides, branch technical position papers, and a series of reports under the label “NUREG” that provide supporting information.

NRC has relinquished its authority to regulate certain radioactive materials, including some radionuclides. As of 1999, twenty-nine states had completed the process to regulate and license the use of radioactive materials in their specific state. These states, which have entered into an agreement assuming this regulatory authority from NRC, are called agreement states. Agreement states, like the NRC, regulate reactor produced radionuclides within their borders and must provide at least as much health and safety protection as under NRC.

As of 1999, NRC maintained approximately 6500 licenses for the use of radioactive materials, and the agreement states maintained approximately 15,000 materials licenses. Every license specifies the type, quantity, and location of radioactive material that may be possessed and used. When radioactive material is transported, special packaging and labeling are required. Also specified in each license are the training and qualification of workers using the materials, specific
procedures for using the materials, and any special safety precautions required. Every licensee is inspected periodically either by NRC or the agreement state to ensure that radioactive materials are being used and transported safely. Violators of regulatory requirements are subject to fines and other enforcement actions, including loss of license.

When used properly, radionuclides are a productive part of today’s world. NRC and the agreement states remain committed to protecting public health and safety in the use of these nuclear materials by inspecting medical, academic, and industrial applications carefully, and monitoring users to ensure safe work practices.

The use of radioactive materials is governed by a license issued by NRC or an agreement state. The licensee not only must satisfy the requirements of the applicable federal or state regulations, but must also implement a site specific program to minimize the potential for radiation exposures. NRC recognizes that effective radiation safety program management is vital to achieving safe and compliant operations. NRC believes that consistent compliance with its regulations provides reasonable assurance that licensed activities will be conducted safely. NRC also believes that effective management results in increased safety and compliance. The licensee is responsible for radiation safety, security and control of radioactive materials, and compliance with regulations. The licensee must implement the elements defined in the license and application as well as comply with current NRC and Department of Transportation regulations. The licensee must establish operating and emergency procedures. The licensee must make a commitment to provide adequate resources (including space, equipment, personnel, time, and, if needed, contractors) to the radiation protection program to ensure that the public and workers are protected from radiation hazards and meticulous compliance with regulations is maintained. The company must select and assign a qualified individual to serve as the radiation safety officer (RSO) with responsibility for the overall radiation safety program.

The licensee must establish appropriate administrative procedures to assure the control of procurement and use of byproduct material. Some licenses are specific and authorize the licensee to perform only certain tasks in a specific manner. On other licenses, termed broad scope licenses, the licensee may use larger quantities of radioactive materials in a variety of applications. In this case the licensee may be required to complete safety evaluations of proposed uses that consider the adequacy of facilities and equipment, training and experience of the user, and operating and handling procedures. As applicable the licensee must review and approve the safety evaluations of proposed uses. Broad scope licensees must specify the duties and responsibilities of management, the Radiation Safety Committee (RSC), and the duties of the RSO. These organizations must review and approve program and procedural changes before the changes are implemented. The RSO must complete periodic audits of licensed operations to determine compliance with the license and applicable regulations. All three functions, management, RSC, and RSO, must take appropriate actions when noncompliance is identified. The licensee is expected to complete an analysis of the cause, corrective actions, and actions to prevent recurrence. Program changes are authorized through use of the license conditions, as long as the program change or revised procedures are reviewed and approved by the RSC prior to implementation. Any change must satisfy regulatory requirements and may not change existing license conditions. The changes must not decrease the effectiveness of the radiation safety program.

A licensee must be familiar with the regulations promulgated by NRC, including but not limited to:

- 10 CFR Part 19, “Notices, Instructions and Reports to Workers: Inspection and Investigations”
- 10 CFR Part 20, “Standards for Protection Against Radiation”
- 10 CFR Part 21, “Reporting of Defects and Noncompliance”
- 10 CFR Part 30, “Rules of General Applicability to Domestic Licensing of Byproduct Material”
- 10 CFR Part 31, “General Domestic Licenses for Byproduct Material”
- 10 CFR Part 32, “Specific Domestic Licenses to Manufacture or Transfer Certain Items Containing Byproduct Material”
- 10 CFR Part 51, “Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions”
- 10 CFR Part 71, “Packaging and Transportation of Radioactive Material”. Part 71 requires that licensees or applicants who transport licensed material or who may offer such material to a carrier for transport must comply with the applicable requirements of the U.S. Department of Transportation that are found in 49 CFR Parts 170 through 189.
- 10 CFR Part 170, “Fees for Facilities, Materials, Import and Export Licenses and Other Regulatory Services Under the Atomic Energy Act of 1954, as Amended”

Each agreement state has equivalent regulations that may be identical or more stringent than the
requirements established by NRC. Each licensee is responsible for determining which regulations apply to a specific operation and implement those elements into each specific program.

**Dose Limits**

Before discussing the various limits and control levels, it is important to understand in which portion of the body limits and controls are applied. Dose limits are based on the risk of exposure to various organs and tissues in the body. The area of the body that contains the vital organs (whole body) has lower allowable doses than those areas of the body containing no vital organs (extremities).

For purposes of external exposures NRC defines the whole body as the head, trunk (including male gonads), arms above and including the elbow, and legs above and including the knee. These are the locations of most of the blood-producing and vital organs.

External exposure results from a radiation source outside the body. Internal exposure is a result of radioactive material being inhaled, ingested, or absorbed through the skin or a wound. NRC dose limits are based on the sum of internal and external exposure.

**Committed and Effective Dose Equivalents**

The NRC dose limit involves the combination of internal and external exposures. The process of combining the two involves the committed dose equivalent and the effective dose equivalent.

**Committed Dose Equivalent**

It is possible to calculate the radiation dose to individual organs after incorporating specific radionuclides into the organ or near the organ. Radioactivity travels to individual organs (depending on its chemical nature) and resides in the organs for a period of time. At some point, the body begins to remove the radioactivity in the organ, and eventually eliminates it.

While the radioactivity is contained in the organs, it is depositing radiation dose in them. The dose equivalent to the organs is committed over the period of time that the body is eliminating the radioactivity. The total dose equivalent associated with an intake of radioactivity is represented by a single value for each organ exposed to the radiation. This total dose equivalent is called the committed dose equivalent.

**Effective Dose Equivalent**

When a human is exposed to radiation from outside of the body, the resulting dose equivalent is typically associated with the whole body. When radioactivity is absorbed into the body, however, the dose equivalent is limited to one or more organs. It is not possible to compare these dose equivalents directly because of the different parts of the body exposed.

To combine these dose equivalents, NRC has adopted a series of weighting factors for the different organs. These weighting factors convert the dose equivalent received by an organ into a comparable dose equivalent to the whole body. This is an effective dose equivalent.

When adjusted to the comparable whole body dose, the internal exposure becomes a committed effective dose equivalent, which can be added to the external exposure that the body has received. The external dose equivalent and the committed effective dose equivalent combined are the total measure of the amount of radiation that has been absorbed. This measure is called the total effective dose equivalent.

The relevant annual occupational dose limits for general employees, as required under NRC regulations (10 CFR Part 20.1201), are shown in Table 23.16.

**ALARA**

A basic radiation protection concept or philosophy in current radiation protection programs is to maintain employee exposure to radiation to as low as reasonably achievable (ALARA). It is

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**Table 23.16 — Occupational Dose Limits**

<table>
<thead>
<tr>
<th>Description Limit</th>
<th>Annual Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total effective dose equivalent</td>
<td>5 rem (0.05 Sv)</td>
</tr>
<tr>
<td>Deep dose equivalent and committed dose equivalent</td>
<td>50 rem (0.5 Sv)</td>
</tr>
<tr>
<td>Eye dose equivalent</td>
<td>15 rem (0.15 Sv)</td>
</tr>
<tr>
<td>Shallow dose equivalent to the skin or extremities</td>
<td>50 rem (0.5 Sv)</td>
</tr>
</tbody>
</table>

**Source:** Code of Federal Regulations, Title 10, Part 20.1201

**Notes:** The 50 rem limit to the skin is designed to prevent nonstochastic effects. Planned special exposures and emergency exposures are considered separately from the above limits.

Radiation dose limits are not restricted simply to radiation workers. Limits for other situations also exist. For example, visitors and members of the public are allowed 0.1 rem (100 mrem) in a year from the sum of internal and external radiation sources.

Extremity means hand, elbow, arm below the elbow, foot, knee, or leg below the knee. Monitoring badges must include the whole body. Higher limits such as a finger dose require separate monitoring.
an application of the LNT hypothesis, which assumes that there is no “safe” dose of radiation. Under this assumption the probability for harmful biological effects increases with increased radiation dose, no matter how small. It is conceivable that if our knowledge of radiation effects expands to the point that a “safe” dose is defined, the ALARA philosophy, as we know it today, would be eliminated. Until such time, it is prudent to keep radiation doses to affected populations (for example, radiation workers, minors, visitors, students, members of the general public, etc.) and discharges to the environment, as low as is reasonably achievable.

Reducing radiation exposures to ALARA levels has long been a goal of radiation safety programs. The concern over possible genetic effects (effects that can be passed from adults to their children) in the 1960s led the Atomic Energy Commission—the predecessor of NRC and DOE, two federal regulatory authorities in the United States—to require that human exposures be kept “as low as practicable” (the “ALAP” philosophy). Additional emphasis on the ALARA philosophy heightened in the 1970s when scientists studying Japanese survivors of the atomic bomb blasts noticed an increased incidence of solid tumors (i.e., tumors other than leukemia). Similar increases also were observed in patients undergoing medical treatments. These increases were associated with very large radiation doses and high dose rates. Unfortunately, the scientists were not able to evaluate whether the same results occurred at small doses. However, ALARA is not a dose limit, but rather a goal. It exemplifies a mindset to achieve radiation exposures that are as far below the applicable limits as is reasonably achievable.

ALARA principles can be utilized in an infinite number of situations. For example, the proper design of a nuclear facility may be modified depending on ALARA considerations. The cost of additional shielding may be justified for an area routinely occupied by members of the public and the corresponding decrease in potential exposure. In addition, designing an X-ray facility for medical applications requires consideration of the amount of shielding needed to ensure that individuals located near the facility (e.g., on the other side of the wall from the X-ray unit) do not receive any more dose than is really necessary during operation of the X-ray device. It is important to place emphasis on the physical design features at a nuclear facility rather than on administrative controls such as procedures or personal practices. The design of a nuclear facility is important in the eventual success of an effective ALARA program. If the facility is designed satisfactorily, worker doses and releases of radioactivity to the environment can not only be controlled but also reduced. An improperly designed facility, on the other hand, may require subsequent modifications, often at considerable expense, to reach the desired dose rates and with a corresponding impact on existing operations.

A successful ALARA program requires an appreciation, understanding, and acceptance from each individual involved in work with radioactivity and radiation-producing machines. More specifically, an ALARA program must have some (preferably all) of the following: a strong commitment from facility management at all levels and throughout the entire organization; dedicated staff; an ALARA program manual or approved program procedures; education and training programs; a well-defined ALARA organization with established responsibilities; a Radiological Safety Committee that reports to upper management on ALARA issues; and routine internal and external audits of the effectiveness of the dose reduction program.

Implementing the ALARA concept involves six basic principles: eliminating or reducing the source of radiation; containing the source; minimizing the time spent in a radiation field; maximizing the distance from a radiation source; using radiation shielding; and using optimization analyses. Eliminating the source of radiation can be accomplished by substituting other appropriate technologies or materials. For example, using an ultrasound exam (sonogram) in prenatal examinations, rather than an X-ray exam, is a much preferred practice due to the type of radiation received by the fetus. The control of contamination on building surfaces, equipment, and so forth is an important ALARA consideration in source reduction. Removing/reducing the source of contamination in turn eliminates (or at least reduces) the likelihood of worker contamination and dose. A subset of source reduction is limiting exposures to radioactive material by containment, ventilation, and filtration. Containment involves using leak-tight or controlled-opening enclosures to prevent radioactive materials from migrating to areas where they are not wanted. Containment may be used temporarily and then removed after the job is complete or be a permanent component (structurally, for example). See the section related to contamination control. Proper ventilation is the flow of air and other gases in a certain direction and rate such that radioactive airborne particles and gases are captured and directed to collection filters, followed by release to the atmosphere once appropriate release limits have been met. A well-designed ventilation system limits the potential for intake of radioactive material. For example, designing the flow of air containing small amounts of radioactive materials away from people helps ensure against unnecessary exposure. To meet ALARA objectives in a radiation protection program, it may be necessary to use some or all of the following items: ventilated fume hoods; glove boxes (used to handle radioactive materials); exhaust systems; water filtration and processing systems; ventilation cleanup systems; and double-walled pipes and tanks; and leak-tight valves.
Minimizing time in a radiation field can be considered the third principle. Simply put, the less time spent in a radiation field, the lower the dose. To meet ALARA goals, no more time should be spent in a radiation field than is necessary to perform the required tasks. Several design factors can be used in a nuclear facility to promote this principle. For example, personnel who have to work in the vicinity of radioactive sources often conduct rehearsals in low dose areas to ensure that they keep their time in the area to a minimum and that they have all the tools they need.

In the case of distance, the farther away from a radiation source, the lower the dose. This is especially true for “point” sources of radiation, which follow the inverse-square law. As with time, several design factors are available to aid in maximizing the distance from radioactive sources. Shielding a radiation source involves the use of different materials placed between the worker and the source to absorb the radiation. The choice of shielding depends on the type of radiation and may either be temporary or permanent. As with time and distance, several design factors are available to reduce worker dose.

Finally, optimization requires that cost-benefit analyses are performed to balance economic considerations with the expected benefits. Optimization is used to demonstrate that any expenses involved—in terms of money, time spent by personnel, dose received, and so forth—are justified in terms of the benefit received. Thus, reducing radiation exposures can be weighed against competing needs (technical considerations, social, operational, and economic).

Working in an area containing radiation and/or radioactive materials requires prejob planning (the extent of which depends on the complexity of the job), implementation of established ALARA controls and tracking of worker doses, and a postjob review to evaluate the “lessons learned.” These steps allow the application of ALARA principles before the job is started, ensure that the principles are being applied correctly, and assist in improving performance on future jobs.

**Radiation Protection**

**External Exposure Controls**

There are several ways to protect oneself from external sources of radiation. However, the three most important ones are the concepts of time, distance, and shielding. The time spent in a radiation field is the first major method for limiting exposure to an external radiation source. To apply this method, it is important to realize that the amount of radiation one receives is directly proportional to the time spent in the radiation field. For example, consider a radiation detection instrument, held in a particular room, that gives a reading of 50 µR/hour. If a worker stands in that location for 1 hour, a total exposure of 50 µR is reached. However, if the person remains in that location for 2 hours, the exposure will increase to 100 µR. On the other hand, if one-half an hour is the total time, the exposure will decrease to 25 µR. Therefore, to minimize the amount of radiation received, the time spent in the radiation field should be kept as short as possible.

Distance alteration is another major exposure-reducing method. A very common and extremely effective way of reducing exposure is to increase the distance from the radiation source. In essence, for photon emitters the exposure drops by the “inverse square” of the distance from the radiation source. If the exposure is 50 µR at 1 foot from a radiation source, the exposure at 4 feet from that same source drops by a factor of 1/42, or 1/16, or 3 µR. As one can see, the distance between a radiation source and a person has an even greater influence over the total exposure than the amount of time one stands in the radiation field. Although the exposure-time relationship follows a direct dependence (i.e., reducing the time spent in a radiation field by one-half reduces the exposure to the worker by one-half), doubling the distance from a source reduces the exposure by a factor of four. It is important to note here that the inverse-square law is observed only when the shape and size of the radiation source is a point source, rather than a line or a cylinder. However, generally speaking, the farther one moves away from a radiation source, the lower one’s exposure will be. The inverse-square law is calculated:

$$I_1 = I_0(D_2/D_1)^2$$

where

- $I_1$ = is the intensity at a distance $D_1$, and
- $I_0$ = is the intensity at a distance $D_2$.

This formula applies to effective point sources but fails when the distances are too close to the source of radiation, where particle radiation may be included for radioactive sources. Remember that particles have a finite range in air. Because sources are labeled with activity and date of that activity for that particular radionuclide, the exposure rate for gamma emitters can be calculated at any distance by use of the specific gamma constant defined as follows.

$$\text{Exposure rate (R/hour)} = \Gamma \frac{A}{d^2}$$

where

- $\Gamma$ = specific gamma ray constant listed in texts in units of R cm$^2$/mCi hour
- $A$ = activity of radionuclide in mCi, and
- $d$ = distance from a point source of radioactivity in cm.
Gamma constants can be found in any standard text or requested from the gamma emitter manufacturer. Diagnostic and therapeutic X-ray machines are calibrated with dose rate exposures at a given distance and field size and in some cases filtration thickness.

Different types of nonphoton radiations can be stopped or “blocked” by using shields constructed of a variety of materials. Alpha particles typically have energies on the order of 4 to 8 MeV. However, they quickly lose this energy through the ionization process. Hence, the range of an alpha particle in a particular type of material is quite short. In fact, a single sheet of paper can be used to completely eliminate the exposure from most alpha radiations. Beta particles lose their energy just like alpha particles—through the ionization process—but they do not ionize to the same ionization density in the absorbing medium as alpha radiation. Therefore, for the same energy particle they have a greater range than an alpha particle in various types of matter. Nonetheless, it is still fairly easy to shield or “block out” beta radiation. For average beta energies of less than 1 MeV, a few inches of wood or a few tenths of an inch of aluminum effectively eliminate the exposure.

Because it is uncharged and electromagnetic in nature, gamma radiation is more difficult to shield than particles such as alphas and betas. Exponential attenuation of gammas implies that some radiation penetrates the barrier. The basic approach to gamma ray shielding is to optimize the thickness and density of the shield such that the intensity of the beam is reduced to an acceptable level, most likely background. In other words, a very thin layer of lead or steel may be just as effective a shield as a much thicker layer of concrete or wood. Neutron shielding is based on “moderating” or slowing down neutrons until their energy is low enough to permit them to be “captured” by a nearby atom. A wide range of shielding materials is used for these purposes, with two of the most common being water or cement.

Charged particle radiations such as alphas and betas travel fixed distances in different materials, with the actual distance depending on their energies (in MeV). The greater the energy, the greater the distance the radiation will travel, and the thicker the shield for a given density must be to stop it. However, shielding for gamma rays and neutrons is more complex. In reality, the range for these radiations is indefinite. It is possible for these radiations to travel for miles before being stopped.

The quantity (amount) of radioactive material (activity measured in becquerel or curie) in the source also influences the exposure received. If one source has only half the amount of radioactivity as another equivalent source, only half the radiation is emitted. Therefore, the exposure rate at a given location away from the small source is only half that of the larger source, not accounting for absorption in the air.

In general, radiation sources are designed to achieve a given purpose. Therefore, reducing the radioactivity in them may not be practical. However, if radiation sources are no longer necessary or needed, it is a good idea to reduce the inventory. Likewise, when residual radioactivity in the form of “contamination” is present, it is clearly prudent to reduce its amount to the greatest extent practical so that the exposure rate from it will likewise be reduced. Therefore, good housekeeping is just as important in the business of radiation and radioactivity as it is anywhere else.

Contamination Control

The purpose of a contamination control program is a structured program designed to reduce internal as well as external radiation exposures that result from the presence of contamination on surfaces of buildings, equipment, and other areas. The goal of a contamination control program is not necessarily to eliminate contamination but to control its spread. An effective contamination control program contains several components including procedural requirements, worker training, the ALARA philosophy, and a quality assurance plan to assure verification.

One key element is classifying and labeling or posting areas with respect to the presence or magnitude of contamination, and whether it is “fixed” or “removable.” As the words imply, fixed contamination means radioactive materials adhere to the surface such that typical handling and touching of that surface does not dislodge the radioactivity. On the other hand, removable contamination is radioactivity that can be easily dislodged or transferred. Areas are often classified according to their contamination levels. The level of contamination control practiced in that area depends on the type and amount of contamination present.

Typical designations include “controlled area,” “contaminated area,” “highly contaminated area,” “airborne radioactivity area,” and “radioactive materials area.” Areas having (or likely to have) loose, that is, removable or transferable surface contamination in excess of specified limits, should be posted in appropriately. Barriers and signs also should be placed at entrances and perimeters around the area to warn personnel of any inherent hazards. The requirements for entering the area also should be posted. Proper posting, followed by training all workers in the meaning of the signs and entrance requirements, serves to limit the spread of contamination and reduces personnel exposures to radiation.

One way to minimize the spread of contamination is to employ covering techniques. Contamination of clean areas can be minimized by covering those areas with materials such as plastic, paper, or strippable coatings. Slightly contaminated areas can be prevented from becoming highly contaminated areas through the use of pro-
tective coverings. Safety hazards are often a factor when selecting a particular type of covering. Polyethylene materials, for example, become very slippery when moisture is present. Flammability is an issue with cloth and polyethylene materials. Coverings placed in high-traffic areas can promote slipping if not securely fastened to the floor. Consideration must be given to all the safety hazards associated with these covering techniques to reduce the need for excessive decontamination while at the same time minimizing cost, time, and excessive exposures. The amount of preparation required to protect an area can vary greatly. Consideration of the type of work and degree of contamination present determines the appropriate type of covering and the number of layers required. Covering techniques, however, should be balanced against the volume of radioactive waste generated, that is, the use of unnecessary amounts of plastic, paper, and so forth, leading to waste disposal problems.

Control of internal exposures is a prime objective for several reasons at sites that use radiation and radioactivity. For one, assessing internal exposures is a much more difficult process than assessing external exposures. In addition, the analysis and interpretation of the results is time-consuming, especially because of regulatory requirements and a relatively new dose reporting system in which both internal and external exposures are summed and reported as one value. Each of these considerations should serve to encourage both worker and line management to minimize internal exposures by controlling the amount and spread of contamination.

Specific contamination control methods will minimize internal exposures. To reduce the possibility of internal contamination, eating, chewing, application of make-up, drinking and/or smoking should be allowed only in designated areas.

Such areas include uncontrolled areas or designated clean areas (permanent/temporary) within controlled areas. Basic contamination control practices dictate that before any individual eats, drinks or smokes, he or she must (1) remove all protective clothing, (2) perform a personal contamination survey and initiate decontamination efforts if necessary, and (3) follow common personal hygiene practices (e.g., washing hands).

The design of a facility, with consideration for proper engineering controls, contributes to controlling contamination and reducing internal exposures. Engineering controls are those that are built into the design of the facility. These include things like ventilation systems with associated filters for trapping particulates and gases. Fume hoods and glove boxes, remote handling devices, and shielding also may be employed as confinement and containment devices. When these fail on occasion or become ineffective, respiratory protection may be required. Of course, restricting entry to contaminated areas only to those who need to be there, and posting these areas appropriately, reduces the probability of contamination and personnel dose. In addition, detection and alarm systems can alert people to changes in the levels of airborne radioactivity, signifying possible loss of contamination control. Contamination on surfaces such as floors, tools, and equipment can be tracked to different locations, spreading the contamination and increasing the possibility of worker exposure. In certain instances transferable contamination on floors can be suspended (the contamination is removed from the floor surface by friction, such as “kicking” or simply walking on the floor) and becomes airborne.

Hot particles may be encountered in some facilities and may make it difficult to limit the spread of radioactive materials. Hot particles are microscopic particles formed from degraded nuclear reactor fuel (fuel “fleas”) or bits of metal that are made radioactive when they are carried by water into the core of a nuclear reactor. Their origin indicates that they pose the greatest concern for operating nuclear reactors. Their small size and high radioactivity demands special contamination controls because they are difficult to detect, yet effective in delivering radiation exposure when they contact the skin. Control of hot particles in the workplace includes both specific procedures tailored to this particular type of contaminant and significant job planning before doing any work in areas where hot particles are known to exist. In addition, special monitoring devices and survey techniques are used to identify and retrieve particles. Controlling their spread by restricting movement of personnel and equipment into hot particle areas is also important. In addition, optimum use of special filters, vacuuming, and wet towel wiping of internal valves and floor surfaces are all effective in reducing the number of hot particles. Typically, only the exposure to a small area on the anterior region of the body is evaluated as a measure of the whole-body exposure. The possibility exists that other more localized areas could have been highly exposed. If an overexposure occurs, it may be necessary to recreate the exposure situation (never the preferred method).

Contamination control points are special areas at nuclear facilities that are equipped with personal clothing racks or lockers; bins stocked with protective clothing; tape; benches; barrels for contaminated trash and protective clothing; step-off-pads; and personnel survey stations (friskers) or personnel contamination monitors. A properly located and equipped control point is necessary for contamination control. The control point typically is positioned with a clear view of the entire work area and positive control of all activities within the area. In addition, the location is chosen so that the flow of personnel and equipment entering or exiting a contamination area can be easily monitored and regulated. Step-off-pads provide an effective method of contamination...
control by serving as the boundary between the contaminated area and the contamination control point. Generally, step-off-pads are considered clean (uncontaminated). They should not be located in areas where a safety hazard may result, such as in stairwells or elevators.

Equipment used in or removed from contaminated areas should be prepared to minimize the spread of contamination. One or more of the following methods may be used: (1) adhesive tape applied to small items such as flashlights or wheels of a handcart; (2) sheet material such as plastic or paper to cover large or bulky items; (3) sleeving for hoses and cables; (4) plastic bags to enclose portable instruments or other equipment that do not provide a remote display; (5) strip-pable coatings to apply to large flat surfaces; or (6) sealing exposed surfaces with paint or other durable coverings. Before removal from a contaminated area, potentially contaminated items must be surveyed for the presence of radioactive contamination.

During the operation of any facility where loose radioactive material is used, contamination is likely to be encountered, and decontamination efforts must be applied. Each technique must be evaluated and modified as necessary, to accommodate the task or item being decontaminated. Decontamination of contaminated tools, equipment, and/or surfaces must be completed before work commences. This approach reduces the likelihood that the contamination will be spread to other uncontrolled areas and also reduces the potential exposure to the employees assigned to the area. A typical scenario includes surveying the item or surface with an acceptable radiation survey instrument; determining whether the contamination is fixed or loose by smear techniques (wipe test); and applying detergents or other agents to the area of interest using a brush or tool to scrub the surface. If the effort is successful, the tools and equipment can be released to the uncontrolled area, and the postings and barriers surrounding the controlled area may be removed. If unsuccessful, the tools and equipment can either be discarded as radioactive waste or placed in a specific area with the appropriate controls and postings. Any liquid or material used to decontaminate the equipment or surface should be tested to determine the correct disposal option. In many situations it is discarded as radioactive waste. Liquids must be absorbed in porous solids before radioactive disposal; mixing with Portland cement, in proportions such that no free standing liquid remains, is a common treatment method.

In cases of personnel decontamination, the method should be selected based not only on the effectiveness of removing the contamination, but also on the effect the method will have on the individual. There are three primary objectives of personnel decontamination: reducing radiation exposure, minimizing the absorption of radionuclides into the body, and preventing localized contamination from spreading to uncontaminated areas. The following steps should be followed when personnel decontamination is required.

- Survey the individual’s skin, hair, clothing, and so forth using an appropriate instrument. If the contamination is widespread, the individual should shower with soap and water and then dry off. The survey should be repeated to verify that the contamination has been reduced to a localized portion of the body. Superficial contamination should always be removed by first washing the affected area with lukewarm water and mild soap. Scrubbing with soft bristle brushes should be done only when absolutely necessary. Hard bristle brushes should not be used because excessive irritation can lead to a loss of integrity of the skin barrier. Hot water, which opens pores such that contamination can enter, or cold water, which closes pores around contamination, should be avoided if possible. In addition, when showering, care should be taken to prevent contaminating body orifices with contaminated runoff. Localized areas often can be decontaminated by taping a surgeon’s glove, plastic bag, or other barrier over the affected area. The contamination is removed by sweating through the skin.
- Contamination present in the eyes, mouth, or wounds should be handled by flushing the areas with copious amounts of water (sterile eye solution for eyes) and relying on trained medical personnel for further decontamination efforts. Potential evidence of internal contamination can be determined by taking nasal swipes with cotton swabs and counting each swab in a GM counter. Based on the preliminary findings, the individual may be asked to blow his or her nose repeatedly; additional nose swabs are then taken and recounted.
- Decontamination efforts should be repeated several times for a given procedure. If after up to four attempts the contamination levels are not being reduced significantly, additional measures should be employed. These include applying mixtures of corn starch or cornmeal with detergent to the affected area. Only if these physical methods fail should the use of chemical agents be considered.
- Detailed records should be maintained that include the initial level and extent of contamination, removal methods, skin condition, and final contamination levels.

**Personal Protective Equipment**

Protective clothing is worn by people working or entering contaminated areas to prevent contamination on their clothes or skin. It provides personnel with an easily removed outer layer, so that if contamination is present on the clothing, the wearer is no longer exposed after the clothing is
removed. In addition, protective clothing may provide some shielding for beta radiation. The amount of protection gained by wearing protective clothing depends to a large degree on how the clothing is worn and used by personnel.

Several types of protective clothing are used depending on the work activity, associated levels of contamination, and whether the contamination is in a dry or wet state. These include lab coats, coveralls (e.g., cotton or Tyvek™), plastic suits, gloves, shoe covers (ranging from cotton to plastic to rubber overshoes), and head gear (e.g., surgeon’s caps and hoods). Instructions should be provided to document the requirements for personal protective equipment and may change depending on conditions encountered in the controlled area.

Protective clothing must be selected to assure that it will fit properly. Clothing that is too large for the wearer makes work more difficult and may drag along the floor, spreading contamination. Clothing that is too small does not give adequate protection, because as the wearer moves, the joints where the clothing meets (i.e., points where coverall sleeves meet gloves) can separate, exposing skin to possible contamination. Protective clothing should be comfortable and provide sufficient mobility for the wearer. An improper fit reduces worker efficiency and could result in increased exposure from increased stay times. Prior to donning, each article of protective clothing should be inspected for contamination, holes, torn seams, missing buttons, broken zippers, and so forth. If defects are found, the item should be marked for repair or discarded, and another article selected. When using rubber gloves, check for small holes to ensure that the glove will not leak. Inflate the glove (not by blowing) to check for air leaks. When selecting gloves, be sure the style used is suitable for the type of work being performed. For example, if “finger tip” type work is to be performed, surgeon’s gloves would be the logical choice. Rubber gloves, which are large and bulky, would not be suitable.

Summary

Human exposure to ionizing radiation is part of the natural coexistence with the planet. Background radiation includes exposure from long-lived radioactive nuclides in the earth, water, and air. With the advent of modern medicine, exposure from dental and medical X-rays, nuclear medicine studies, and radiation therapy have added to the accumulated exposure for both the patient and the occupational worker. Industrial and consumer products add to the body burden. Radiation limitation levels are set for the occupational worker, with more limited measures taken for the general public reduced by a factor of 10 or more. The accumulated knowledge of the biological effects of radiation, the collection of which spans more than a century, is reviewed by government agencies and is eventually translated into radiation protection for the worker and the general public.

Additional Sources of Information


National Council on Radiation Protection and Measurements (NCRP): Control of Radon in Houses (NCRP rep. 103). Bethesda, MD: NCRP.


References


