GOALS

When you have mastered the content of this chapter, you will be able to achieve the following goals:

Definitions
Define each of the following terms, and use each term in an operational definition:
- fission
- chain reaction
- critical mass
- moderator
- breeder reactor
- neutron activation
- fusion
- thermonuclear reaction
- plasma
- "magnetic bottle"
- tracer
- biological half-life
- effective half-life

Fission Reactors
Explain the operation of a nuclear fission reactor.

Radiation Detectors
Compare different nuclear radiation detectors and their uses.

Radiation Problems
Solve problems involving radiation applications using biological half-life and dosage data.

Tracer Applications
Outline the use of radioactive tracers in medical applications.

PREREQUISITES

Chapter 32
Applied Nucleonics

32.1 Introduction

What are the conditions necessary for a self-sustaining chain reaction? What are the basic requirements for a nuclear reactor? Why is nuclear fusion a process that is considered promising for meeting future energy needs? The answers to these questions involve the applications of the nuclear fission and fusion processes. In this chapter you will study such applications.

What are the basic ways of producing artificial radioactive materials? What are some of the uses of radiation in medical diagnosis and treatment? Some techniques and the physical basis for the use of radiation in nuclear medicine will be presented in this chapter. Your understanding of these nuclear applications will provide a basis for your evaluating the potential of new developments in nuclear medicine and technology.

32.2 Nuclear Fission

The discovery of nuclear fission in 1938 by Hahn and Strassman suggested the possibility of tapping the energy of the nucleus. Recall that it is a conversion of some of the nuclear binding energy into kinetic energy that characterizes both fission and fusion. The basis of this conversion can be seen from the binding energy per nucleon curve which was shown in Figure 31.1. It was noted that if a heavy nucleus is split, the resultant nuclei are in the middle of the curve. In this middle region the average binding energy per nucleon is about 8.5 MeV as compared with 7.5 MeV per nucleon for the heavy nuclei like uranium. This corresponds to the mass difference that accounts for an energy release of about 1 MeV for each nucleon involved in the process.

The fission reactions that were studied first involved the use of the neutron bombardment of the fissionable material. The theoretical explanation for the process was first suggested by Niels Bohr and John A. Wheeler in 1939. They suggested that the fission of uranium was associated with the $^{235}_{92}$U isotope rather than the much more abundant $^{238}_{92}$U. They suggested that the $^{238}_{92}$U nucleus has low stability, and that after capturing a slow neutron the $^{235}_{92}$U divides into two nuclei of roughly the same size. The key to the usefulness of the fission reaction is its potential for a self-sustaining chain reaction. The chain reaction is possible because each fission releases some neutrons. If these neutrons are captured by other fissionable nuclei, the chain reaction can become self-sustaining with a tremendous release of energy.

The criterion that must be met for a nuclear fission explosion is that the surface area to volume ratio must be such that enough neutrons produce fissions to sustain the chain reaction. This condition leads to the concept of critical mass for the fissionable material. This is the mass of material that will capture just enough neutrons to maintain the chain reaction.
reaction. It should be noted that the fission process is analogous to the break up of a liquid drop. The product nuclei (droplets) are not unique, and the number of neutrons released during fission depends upon the particular fission reaction that occurs. In each fission reaction two or more neutrons are emitted. The average for the $^{235}\text{U}$ reaction is about 2.5 neutrons per fission. If the fission reaction is to be used in slow energy release applications, it is necessary to be able to control the rate of energy release. There are three controllable physical parameters: the purity of the fissionable material (impurities tend to absorb neutrons and thereby reduce chances for a chain reaction); the production of thermal neutrons; and the mass of the fissionable material. For a bomb it is a matter of combining two subcritical masses (each of high purity) to make a critical mass for a nuclear explosive chain reaction (this takes approximate $10^6$ sec).

For a nuclear-fission reactor the key factor lies in the ability to insert control rods of neutron absorbing material (such as boron or cadmium) which have very high interaction probabilities for thermal neutrons. With these control rods the neutron flux can be maintained at the desired level. A moderator material is used to slow down the fast neutrons from the fission reaction. The properties of the moderator that are important are its low nuclear mass-so that neutron collisions rapidly reduce the neutron energy-and low neutron absorption probability. Two good moderator materials are heavy water ($\text{D}_2\text{O}$), and carbon (graphite blocks). A diagram of a nuclear fission reactor is shown in Figure 32.1.

The nuclear fission reactor has been used as a source for heat energy. The most common use of this heat energy is in the generation of electrical energy using conventional steam turbine technology Figure 32.2. The nuclear reactor has also been developed into the energy source for submarines and large ships. Unfortunately, development of small, portable nuclear-energy sources for use in homes and automobiles seems unlikely. In fact, many people are concerned about the hazards of nuclear electrical generators and the benefit vs risk debate on the use of nuclear energy to generate electrical power still rages.

In addition to the energy output of the fission reactor, it is possible for a reactor to produce more fuel (fissionable material) than it consumes. These breeder reactors are
possible because of neutron capture by $^{238}_{92}\text{U}$ (the most abundant isotope of uranium) leads to the creation of $^{239}_{94}\text{Pu}$. Plutonium-239 is fissile by slow neutrons and becomes new nuclear fuel. The half-life of $^{239}_{94}\text{Pu}$ is 24,000 years. What can you conclude about the presence of $^{239}_{94}\text{Pu}$ in natural ores?

### 32.3 Nuclear Activation Analysis

A nuclear fission reactor can be used as a neutron source. The neutron flux from a reactor is a useful research tool. The neutrons can be used to bombard nonradioactive materials and thereby create artificial radioactive isotopes by neutron capture. Such neutron capture is the basis of neutron activation analysis. Neutron activation analysis can be used to identify constituents of a sample. The sample is bombarded with neutrons, and the components capture neutrons and become radioactive beta emitters. The radiation is monitored and is characteristic of a particular radioisotope. For example, a sample of $^{23}_{11}\text{Na}$ will capture a neutron to produce $^{24}_{11}\text{Na}$, which has a half-life of 15 hours. The presence of $^{23}_{11}\text{Na}$ is detected by the measurement of the $^{24}_{11}\text{Na}$ present in the sample. Quantities as small as $10^{-9}\text{ g}$ of some elements can be detected by neutron activation analysis.

### 32.4 Nuclear Fusion

Although the energy from both the fission and fusion reactions results from conversion of nuclear binding energy to kinetic energy, the two processes have some important differences. The Coulomb repulsive force assists the fission reaction while it represents an energy barrier for the fusion reaction. The fusion reaction requires energy input equivalent to thermal energies corresponding to 100 million degrees celsius. For this reason the fusion reaction is also called a thermonuclear reaction. At these high temperatures all of the electrons are stripped off of the atoms of the reactants, and the result is a plasma of bare nuclei (positive) and electrons (negative). For a thermonuclear bomb it is possible to generate the necessary temperatures for fusion with a small fission bomb. The result is a bomb with greater energy release than possible from just a fission bomb.

This solution is obviously not applicable to a controlled fusion reactor. The sun uses gravitational collapse to generate the temperatures necessary for fusion, but this is not possible in the laboratory. One approach has been to create a plasma by stripping off...
electrons and to squeeze the plasma in a strong magnetic field (called a magnetic bottle) in an attempt to get densities great enough to sustain a fusion reaction. Thus far, reaction times have been limited to the order of microseconds. There is currently much interest in the possibility of using a high-energy laser beam focused on a fuel pellet, such as solid hydrogen.

The fusion reactor, if perfected, offers several advantages over fission. These advantages include:
1. an abundance of fuel ($^2\text{H}$ from water)
2. very low levels of radioactivity
3. the possibility of direct conversion into electrical energy

The problems associated with fusion reactors are difficult to solve, but the potential of fusion is beginning to receive more attention of research funding government bodies everywhere. (During the 1960s more money was spent for white side wall automobile tires in one year in the United States than was spent for fusion research.)

### 32.5 Applications of Radioactive Isotopes

There are many applications of artificially produced radioactive isotopes see Table 32.1. Such isotopes are made by neutron bombardment of stable nuclides as previously described. One of the most widely used isotopes is $^{60}\text{Co}$ which is produced by the capture of a neutron by stable $^{59}\text{Co}$. Cobalt-60 is a beta emitter which emits gamma radiation of 1.17 MeV and 1.33 MeV in the course of beta decay. These gamma rays can be used for radiation therapy in the treatment of tumors. In some cases the $^{60}\text{Co}$ is implanted in the tumor in the form of a needle. Such implants usually have an activity of 100 millicuries or less. Cobalt-60 is used to some extent for radiographs. It is also used in the diagnosis of certain blood disorders. Vitamin $\text{B}_{12}$ which has been tagged with $^{60}\text{Co}$ is administered orally and the urine is checked for radioactivity. In patients with chronic myelogenous leukemia the clearance of $\text{B}_{12}$ from the digestive tract is slowed. This can be checked with the $^{60}\text{Co}$ tagged vitamin.
## Table 32.1
Characteristics of Some Radioisotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Radiation</th>
<th>Radiation Energy (MeV)</th>
<th>Half-life</th>
<th>Some Uses and Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>$\beta^-$</td>
<td>0.0180 particle</td>
<td>12.25 yr</td>
<td>Tagging drugs, hormones, vitamins</td>
</tr>
<tr>
<td>$^14$C</td>
<td>$\beta^-$</td>
<td>0.158 particle</td>
<td>5770 yr</td>
<td>Tagging drugs, hormones, vitamins</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>$\beta^+$ (97%)</td>
<td>0.65 particle</td>
<td>1.87 hr</td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>$\beta^-$</td>
<td>1.33 particle</td>
<td>15 hr</td>
<td>Radiocardiology, blood flow</td>
</tr>
<tr>
<td>$^{24}$P</td>
<td>$\beta^-$</td>
<td>1.71</td>
<td>14.3 d</td>
<td>Treatment of diseases of the blood, bone marrow; wide application</td>
</tr>
<tr>
<td>$^{35}$S</td>
<td>$\beta^-$</td>
<td>0.167 particle</td>
<td>85.7 d</td>
<td>Tagging amino acids</td>
</tr>
<tr>
<td>$^{35}$K</td>
<td>$\beta^+$ (22%)</td>
<td>3.53 particle (82%)</td>
<td>12.4 hr</td>
<td>Breast neoplasms; potassium composition in body parts</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>2.03 particle (18%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{45}$Ca</td>
<td>$\beta^-$</td>
<td>0.66 particle (63%)</td>
<td>4.7 d</td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>1.516 $\gamma$-rays (18%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>0.50, 0.234, 0.48, 0.83, 1.31 $\gamma$-rays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{51}$Fe</td>
<td>$\beta^-$</td>
<td>0.46 particle (58%)</td>
<td>45 d</td>
<td>Physiology of the blood; plasma increases in persons with anemia, polycythemia, and leukemia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.27 particle (48%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.56 particle (0.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.145, 0.191 $\gamma$-rays</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.337, 1.102, 1.290 $\gamma$-rays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{65}$Zn</td>
<td>Electron capture</td>
<td>0.67 particle (19%)</td>
<td>9.3 hr</td>
<td>Scanning</td>
</tr>
<tr>
<td></td>
<td>$\beta^+$</td>
<td>0.04 particle (19%)</td>
<td></td>
<td>Scanning</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>0.04 $\gamma$-rays</td>
<td></td>
<td>Scanning</td>
</tr>
<tr>
<td>$^{65}$Zn</td>
<td>Electron capture</td>
<td>2.36 particle (93%)</td>
<td>38.3 m</td>
<td>Scanning</td>
</tr>
<tr>
<td>$^{66}$Ga</td>
<td>$\beta^+$</td>
<td>1.80 particle (95%)</td>
<td>68 min</td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td></td>
<td>Electron capture</td>
<td>0.81 $\gamma$-rays</td>
<td></td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>1.06 $\gamma$-rays</td>
<td></td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>1.24 $\gamma$-rays</td>
<td></td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>1.88 $\gamma$-rays</td>
<td></td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td>$^{68}$As</td>
<td>$\gamma$</td>
<td>0.286 $\gamma$-rays</td>
<td>8 sec</td>
<td>Diagnosing and locating brain tumors</td>
</tr>
<tr>
<td>$^{74}$Se</td>
<td>Electron capture</td>
<td>0.024 to .280 $\gamma$-rays</td>
<td>120 d</td>
<td>Cancer of pancreas</td>
</tr>
<tr>
<td>$^{75}$Se</td>
<td>Isomer transfer</td>
<td>0.150 $\gamma$-rays (88%)</td>
<td>70 min</td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td></td>
<td>Electron capture</td>
<td>0.225 $\gamma$-rays (15%)</td>
<td></td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>0.233 $\gamma$-rays (1%)</td>
<td></td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>0.008 $\gamma$-rays (1%)</td>
<td></td>
<td>Detection of bone disorders</td>
</tr>
<tr>
<td>$^{84}$Sr</td>
<td>$\beta^-$</td>
<td>1.46 particle (100%)</td>
<td>80.4 d</td>
<td>Treatment of bone tumors</td>
</tr>
<tr>
<td>$^{85}$Sr</td>
<td>$\beta^-$</td>
<td>0.54 particle (100%)</td>
<td>28 yr</td>
<td>Treatment of benign tumors on white of eye</td>
</tr>
</tbody>
</table>
Another approach used in radioactive isotope therapy is based on the biochemistry of the body and the selective localization of specific isotopes. For example, $^{131}\text{I}$ is localized in the thyroid, $^{32}\text{P}$ is concentrated in bone, $^{42}\text{K}$ is localized in muscle, $^{35}\text{S}$ is localized in the skin, and $^{59}\text{Fe}$ is concentrated in the blood. In addition to radiation therapy, these isotopes can be used as tracers. Tracer studies allow the scientist to track biochemical processes by following the radioactive tracer through the body. For example, Melvin Calvin was awarded a Nobel Prize for his work using $^{14}\text{C}$ to unravel the photosynthesis reactions. The uptake of iodine-131 by the thyroid can be monitored, and the functioning of this organ can be evaluated.

Ingested iodine-131 is also used therapeutically to destroy cancerous tissue in the thyroid and to treat hyperthyroidism and certain cases of heart disease.

Other radioisotopes are used to diagnose and treat abnormal situations. It is possible, by selecting the proper isotope that emits the desired radiation at the correct energies, to selectively destroy certain tissues or organs and leave adjacent areas with little or no damage.

An important consideration in using injected radioactive isotopes is the biological half-life of the isotope. The biological half-life is the time required for one-half of the biochemically active isotope to be eliminated by natural processes. Assuming the biological process is exponential, we find the following equation giving effective half-life $T$ in terms of the biological half-life $T_b$ and the radioactive half-life $T_r$:

$$1/T = 1/T_b + 1/T_r \quad (32.1)$$

The activity of a sample is equal to the number of nuclei present $N$ times the number of disintegrations the isotope makes in one second,

$$A = N\lambda \quad (32.2)$$

where $\lambda$ is the disintegration constant from Chapter 31.

$$N = N_0e^{-\lambda t} \quad (31.12)$$
EXAMPLES

1. Find the amount of cobalt-60 necessary for a 100-millicurie needle. The half-life of $^{60}_{27}\text{Co}$ is 5.24 yr.

$$A = N\lambda$$

where

$$\lambda = \frac{0.693}{t_{1/2}}$$

$$= \frac{0.693}{5.24 \times 3.17 \times 10^7 \text{ sec}} = 4.2 \times 10^{-9} \text{ sec}^{-1}$$

Thus

$$A = 100 \times 3.7 \times 10^7 \text{ dis/sec} = N \times 4.2 \times 10^{-9} \text{ sec}^{-1}$$

$$N = \frac{3.7}{4.2 \times 10^{18} \text{ nuclei}} = (M/60) \times 6.02 \times 10^{23}$$

$$M = 8.78 \times 10^5 \text{ g for 100 millicurie of } ^{60}_{27}\text{Co}$$
2. The effective half-life of iron-59 is 27 days, and its radioactive half-life is 46 days. Find the biological half-life of $^{59}_{26}$Fe.

$$\frac{1}{T} = \frac{1}{T_b} + \frac{1}{T_r} = \left(\frac{1}{T_b} + \frac{1}{46}\right) \text{ days}^{-1}$$

$$\frac{1}{T_b} = (\frac{1}{27} - \frac{1}{46}) \text{ days}^{-1}$$

$$T_b = 65.4 \text{ days}$$

Some of the radioactive isotopes with their effective half-lives are listed in Table 32.2. Note that certain isotopes tend to concentrate in particular parts of the body.
EXAMPLES

1. Radioactive iodine, $^{131}\text{I}$, is used in medical diagnosis. Iodine-131 has a half-life of approximately eight days. A sample of this isotope has an activity of 20 microcuries when administered to a patient.

a. Find the activity of this material four days later.

$$A_4 = A_0 \exp\left(-\frac{0.693 \times 4}{8}\right) = 20 \exp(-0.693 \times 4 / 8) = 20 \times 0.707$$

$$A_4 = 14.1 \text{ microcuries}$$

b. How long will it take for the activity to drop to 1 percent of its initial value?

$$A_t = 0.01 A_0 = A_0 \exp\left(-\frac{0.693}{8} t\right)$$

$$\exp(-0.693 t / 8) = 0.01$$

$$\exp(0.693 t / 8) = 100$$

$$0.693 t / 8 = \ln 100$$

$$t = 53.2$$

2. By injecting a known volume of a specific activity serum into the blood of a subject, it is possible to determine the volume of the subject’s blood. After allowing a short time for the serum to mix completely (10 to 30 minutes) a blood sample is taken. The specific activity of the sample is measured. The specific activity is equal to the total activity divided by the total blood volume of the subject. From this relation the blood volume can be determined.

Four cubic centimeters of serum with 100-microcurie/cm³ specific activity is injected into a subject. Twenty minutes later a blood sample is taken and its specific activity is found to be 0.038 microcuries/cm³. Find the blood volume of the subject.

total activity of injected serum = $4 \text{ cm}^3 \times 100 \mu\text{C/cm}^3 = 400 \mu\text{C}$

final specific activity = $0.038 \mu\text{C/cm}^3 = 400 \mu\text{C/V}$

where $V$ is the total volume of blood. Thus the volume of blood is

$$V = \frac{400}{0.038 \text{ cm}^3} = 1.05 \times 10^4 \text{ cm}^3$$

Note: We have assumed that the activity at the time of sampling is the same as when the serum was injected. What conditions are necessary for this approximation to be acceptable? Iodine-131 is frequently used for these measurements. Its half-life is 8 days. Is the approximation a good one for this case?

The applications of radioisotopes are not limited only to medical uses. They are broadly used in other fields of endeavor. Some examples are:
AGRICULTURE
a. animal husbandry: nutrition studies by tracers, diet additives, biochemistry of milk production
b. plant physiology: mechanism of photosynthesis, soil fertility, uptake of fertilizers

ARCHAEOLOGY
Carbon dating of deposits

ASTRONOMY
solar energy from nuclear processes

BOTANY
transport of fluids
photosynthesis research

CHEMISTRY
synthesis of new elements
alchemy reaction
mechanisms

ENGINEERING
radiology
thickness tests
friction studies

FOOD PROCESSING
preservation of foods

METALLURGY
atomic diffusion studies

GEOLOGY
well logging
mineralogy: color change of crystals by radiation
32.6 Geiger-Müller Tube

All of the uses of radiation require the ability to measure radiation levels. One of the most widely used detectors is the Geiger-Müller tube described briefly in Chapter 30. The G-M tube is gas filled and has a high voltage applied between its cylindrical conducting wall and a coaxial central electrode, as shown in Figure 30.5 on page 676.

When radiation enters the tube, it produces ionization in the gas inside the tube. The ions created are accelerated by the high voltage applied across the tube. These accelerating ions will create other ions upon collisions with gas molecules, and thus an amplification of $10^6$ to $10^7$ is achieved. This ionization pulse creates a current pulse across the resistor for each incoming particle that produces ionization. The G-M tube is designed to measure radiation intensity. It is capable of detecting all forms of ionizing radiation. The G-M tube is relatively slow with a resolving time (time between just resolvable pulses) of about $10^{-4}$ seconds. (This means a 5 percent loss at count rates of only 100 counts per second.) The G-M tube is not as efficient for gamma ray photons as it is for charged particles. A block diagram for a G-M tube detecting system is shown in Figure 32.3.

32.7 Scintillation Counter

A much more efficient photon detector is the scintillation counter which we introduced in Chapter 30. A typical scintillator and photomultiplier tube apparatus is shown in Figure 30.6 on page 677. The scintillator crystal of sodium iodide doped with thallium absorbs the high-energy photons and radiates light in the visible or ultraviolet region. These secondary photons enter the photomultiplier (PM) tube where they strike a photocathode, and upon the absorption of the photons, the photocathode emits electrons.

These photoelectrons are accelerated by the high voltage between the electrodes (called dynodes) in the photomultiplier tube. The overall amplification of the PM tube may be the order of 107. This scintillator-PM tube combination not only detects gamma rays and x rays, but it can also be calibrated so that the current pulses are proportional to the energy of the original photon. There are some applications for which this energy discrimination ability is quite useful.
32.8 Thermoluminescence Dosimetry

Some insulators have traps for electrons created by radiation. One such insulating crystal is lithium fluoride LiF doped with manganese or europium. In thermoluminescence dosimetry (TLD) the crystal is exposed to the radiation to be measured. Then at a selected time the crystal is heated. The thermal energy releases the electrons from the traps. As the electrons make transitions to lower energy states the crystal emits photons. The total number of photons emitted is proportional to the intensity of the radiation incident on TLD crystals. The LiF crystal has radiation absorption characteristics similar to those of living tissue.

32.9 Charged-Particle Detectors

Specially doped germanium and silicon crystals can be made into very sensitive charged-particle detectors. A schematic diagram of a typical surface barrier silicon detector is shown in Figure 32.4. The incoming charged particle creates electron-hole pairs that in turn create a pulse in the external circuit current as shown in the figure. These solid-state detectors are very efficient and can be calibrated to give excellent energy discrimination for the incoming charged particles. In addition, they have very fast response times (~10⁻⁹ sec).

32.10 Film Exposure

One of the oldest detectors of radiation is the photographic emulsion. The incoming radiation exposes the film and produces an optical density that is proportional to the intensity of radiation exposing the film.

The optical density is defined in the following equation:

\[ \text{OD} = \log_{10} \frac{I_o}{I} \quad (32.3) \]

where \( I_o \) is the reference light intensity and \( I \) is the intensity of the light that passes through the exposed film.

A diagram of a densitometer used to measure the optical density of the exposed film is shown in Figure 32.5. Note there is a region where OD is proportional to the exposure (intensity x time).
EXAMPLE

A radiogram (photographic record of radiation) shows an optical density of 2 for a known exposure $E$, an unknown exposure produces an OD of 2.5. Find the unknown exposure $E'$ in terms of the given value $E$.

$$2 = \log_{10} I_{0}/I$$ and $2 = k \times E$

Thus,

$$2.5 = k \times E'$$

and

$$E' = \frac{2.5}{2.0}E = 1.25E$$

32.11 Shielding

The term shielding has come to mean a system to control radiation hazards around nuclear facilities and other radiation producing devices. The purpose of the shielding is to reduce the intensity of the radiation to an acceptable (nonhazardous) level. The biological dose uses the concept of flux. The flux is expressed of number per square centimeter per second. For example, for x rays it is the number of photons per square centimeter per second, and for neutrons it is the number of neutrons per square centimeter per second. The shielding should be designed to attenuate the radiation or to convert the energy to an innocuous form, generally heat.

Different processes are used in shielding, and the specific process for each case depends upon the type of radiation and its energy. The nature of radiation suggests the type of shielding to be used. In general the radiation can be divided into the following four areas:

1. HEAVY CHARGED PARTICLES: All heavy charged particles (a-particles, protons, etc.) have similar interaction with matter, principally with electrons. High density materials can be used for shielding. The major concern of biological shielding for these types would be high-energy particles from accelerators.
2. BETA PARTICLES: The beta particles (both + and -) of the energy range of most radioisotopes are fairly easily to control by even low-Z materials. That is, a thickness of 7 mm (1/4 inch) of such material as aluminum, Lucite, or Plexiglas is sufficient. However, high-energy electrons from accelerators present a much greater problem. For these the control of the Bremsstrahlung produced in the shield becomes the major problem. The methods of photon shielding are used for these rays.

3. PHOTONS: To shield for x and γ rays the most effective materials are those with high electron density, that is, high Z. The economics of the situation then becomes important: You want to select the material which is cheapest per unit mass which will do the job. You then calculate the needed thickness. Some of the materials that are used for photon shields are concrete, earth, iron, and lead.

4. NEUTRONS: The shielding desired for neutrons depends upon the neutron energy. Fast neutrons are best attenuated by interaction with heavy nuclei. For low-energy neutrons you need material made of materials with low Z, hence something that has a high concentration of hydrogen nuclei. Paraffin is used for low-energy shielding. For neutrons of mixed energies you need mixed materials. Concrete is a definite possibility as it has both the heavy nuclei and the hydrogen nuclei. Water is also used for neutron shielding.

In cases where shielding is impractical, sources of radiation can be placed at greater distances from human populations. The plans to bury nuclear reactor wastes in salt mines or under the ocean is based on the shielding properties of earth and water and on the inverse square law that relates the energy density of radiation at some location to the distance from that location to the source of radiation. The energy density at a point in joules per unit area is proportional to the reciprocal of the square of distance from that point to the source of radiation. For example, if you double the distance between your body and a radiation source, the amount of radiation energy you receive will be reduced to a level of one-fourth of that at the original distance.

\[ \text{energy/area} \propto \frac{1}{(\text{distance to source})^2} \]  

(32.4)

**SUMMARY**

Use these questions to evaluate how well you have achieved the goals of this chapter. The answers to these questions are given at the end of this summary with the number of the section where you can find related content material.

**Definitions**

Write the correct word in each blank.

1. In order for a nuclear fission reaction to be self-sustaining there must be a ________ of fissionable material present, and a ________ must occur in which each fission of a nucleus releases some neutrons to continue the process. If the nuclear fission process used in a reactor process is one that produces more nuclear fuel, it is called a ________.
2. A fusion reaction which can be confined by large magnetic fields in a _______ is also called a _______ and involves the _______ of _______ nuclei to produce _______ nuclei.

3. The rate of fission energy release can be ___________ by the use of ___________.

4. Nuclear fission reactors can be used to produce __________ , ___________ and __________.

5. The _______ from a reactor can be used to produce _______ and to cause substances to become beta emitters so that their presence can be detected down to _______ g by means of _______ _________.

6. The biological half-life of a system is ____________.

Fission Reactors

7. What are the basic principles of a nuclear fission reactor? Sketch a block diagram one as you envision it.

8. List two detectors for each of the following: α- particles, β-particles, γ-rays, protons, neutrons.

Radiation Problems

9. What energy absorption rate results from an implant of 1.2 millicuries of radioactive palladium (Pd) per gram of tissue? The half-life of palladium-103 is 17 days. This isotope decays by electron capture with an emission of 0.57 MeV in g radiation per disintegrating atom. Assume all energy is absorbed in adjoining tissue.

Tracer Applications

10. List three specific applications of radioisotopes as tracers.

Answers

1. critical mass, chain reaction, breeder reactor (Section 32.2)
2. magnetic bottle, thermonuclear reaction, combining, light, heavy (Section 32.4)
3. controlled, moderators (Section 32.2)
4. heat energy, additional fuel, neutrons (Sections 32.2, 32.3)
5. neutrons, artificial isotope tracers, 10-9, neutron activation analysis (Sections 32.3, 32.5)
6. time required for one-half of the isotope to be eliminated from a biological process (Section 32.5)
7. see Section 32.2
8. see Sections 32.6, 32.7, 32.8, 32.9, 32.10
9. 4.05 x 10⁻⁶ J/g-sec. (Section 32.5)
10. see Section 32.5 and Tables 32.1 and 32.2)
ALGORITHMIC PROBLEMS

Listed below are the important equations from this chapter along with two from Chapter 31. The problems following the equations will help you learn to translate words into equations and to solve single-concept problems.

Equations

\[
\frac{1}{T} = \frac{1}{T_b} + \frac{1}{T_r} \quad (32.1)
\]

\[
A = N\lambda \quad (32.2)
\]

\[
\text{OD} = \log_{10} \frac{I_0}{I} \quad (32.3)
\]

energy/area \propto \frac{1}{(\text{distance to source})^2} \quad (32.4)

\[
t_{1/2} = \frac{0.693}{\lambda} \quad (31.13)
\]

\[
A = A_0 e^{-\lambda t} = A_0 e^{-0.693 t / t_{1/2}} \quad (31.15)
\]

Problems

1. What is the biological half-life for $^{131}\text{I}$? (See Table 32.2)

2. What is the disintegration constant for a nuclide ($^{32}\text{P}$) which has a half-life of 14.3 days?

3. If one has originally the same amount of two radioactive materials, one finds that sample A originally has much greater activity than sample B. A few days later he finds that sample B has a greater activity than sample A. Explain.

4. A radioactive capsule of Iodine-131 is rated 2.00 microcuries. When should the rating become 0.500 microcurie?

5. Two patients are placed at distances of 1 m and 3 m from a radioactive point source. How will their dosages compare?

Answers

1. 120 days
2. $5.61 \times 10^7 \text{ sec}^{-1}$
3. 16 days
4. 9:1
EXERCISES

These exercises are designed to help you apply the ideas of a section to physical situations. When appropriate the numerical answer is given in brackets at the end of the exercise.

Section 32.2

1. Outline the operation of a nuclear fission reactor, and suggest where you would put safety controls and indicate the nature of controls you would employ.

Section 32.5

2. Using Table 32.2, find the biological half-life for each of the following isotopes: $^3$H, $^{35}_{16}$S, and $^{59}_{26}$Fe. [19.1 days, 22.7 days, 65.4 days]

3. Outline a procedure that might be used to measure the red blood cell count in a subject. (*Hint*: red blood cells concentrate iron biochemically.)

4. Suppose that a woman has $10^9$ curie of strontium-90 in her bones. Strontium-90 emits beta particles with a total energy of 2.75 MeV. Assume all of this energy is absorbed in the 1.00-kg bone. Calculate the dosage this woman will get in one year. (Assume radiation is constant since half-life is 28.0 yr.) [4.32 x 10^{-4} J, 43 mrem]

5. Derive Equation 32.1 using the assumption that the biological half-life of an isotope is governed by the exponential decay law analogous to radioactivity.

6. Find the mass of $^{131}_{53}$I giving an activity of 10 microcuries. The half-life of $^{131}_{53}$I is 8 days. [0.8 x 10^{-9} g]

Section 32.11

7. What are the ways in which neutrons may interact as they pass through a tissue? What method of protection would you recommend against a powerful source of neutrons?

8. What would you recommend as shielding for
   a. rays
   b. β particles
   c. neutrons
   d. α particles
PROBLEMS

The following problems may involve more than one physical concept. When appropriate the numerical answer is given in brackets at the end of the problem.

9. Given the following information, how many curies are there in 1 gram of substance?

<table>
<thead>
<tr>
<th>Radioactive Isotope</th>
<th>Type of Emission</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}$P</td>
<td>β-particle</td>
<td>14.3 days</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>β-particle</td>
<td>15 hours</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>β-particle</td>
<td>28 years</td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>β-particle</td>
<td>8.05 days</td>
</tr>
</tbody>
</table>

[P, 2.9 x 10^5 curies; Na, 8.7 x 10^6 curies; Sr, 140 curies; I, 1.27 x 10^5 curies]

10. A beam of b-rays or g-rays can be used to locate foreign body in a tissue. As an example, the source (small) to film distance is 80.0 cm and two exposures are taken on the film. A marker is placed on the upper skin of the patient between the foreign body and the source. If the source is moved a horizontal distance of 10.0 cm, the image of the foreign body and marker are displaced 10.7 cm and 2.5 cm respectively. What is the vertical distance between the marker and foreign body? [16 cm]

11. Zinc-69 decays from an excited nuclear state by gamma emission with a half-life of 1.38 hours and a gamma ray energy of 0.400 MeV.
   a. Find the mass difference between the ground state and the excited state of this nucleus.
   b. Find the maximum energy that such a gamma ray might transfer to an electron through Compton scattering. [a. 7.1 x 10^{-31} kg; b. 0.243 MeV]

12. What is the activity of potassium-40 in an 80-kg person under the following conditions: 0.35 percent of the person is potassium, and 1.2 percent of the potassium is $^{40}$K. Potassium-40 is a β emitter and has a half-life of 1.27 x 10^9 years. [8.6 x 10^5 disintegrations/sec]

13. If only two percent of a given radiation is transmitted through 20 cm of soft tissue, what is the effective absorption coefficient of the tissue? Assume homogeneous radiation. What thickness would reduce the beam to half its original intensity? [1.96 x 10^{-1} cm^{-1}, 3.5 cm]

14. What is the photon flux at a distance of 1 m from a 500-millicurie point source gamma ray emitter? Assume one photon per disintegration. [1.45 x 10^9 photons/m^2 sec]

15. Radioactive cobalt-60 is used in the treatment of some diseases. It decays by emitting two gamma rays of energy 1.17 MeV and 1.33 MeV. The half-life is 5.26 years. Assume there is 1.00-g source and that one percent of the emitted gamma rays strike the patient, the patient’s mass is 70.0 kg, and exposure lasts for 3.00 minutes. What is the energy absorbed per kilogram per second? What is this in rads? [2.38 x 10^6 J/kg-sec, 42.9 rad]
16. One of the newest isotopes to receive considerable use is technetium-99 ($^{99}_{43}$Tc). This isotope has a 6-hour half-life as it decays by 0.14 MeV gamma rays from an excited state to its ground state. Assume that 50 millicuries of $^{99}_{43}$Tc is injected into the body, and that one-half of the radiation is absorbed in the 50-kg body of the patient. Find the dosage received by the patient. [4.1 x $10^{-7}$ J/kg-sec]

17. The average energy released in a fission of $^{235}_{92}$U nucleus is about 180 MeV. Suppose we had 1.00 g of $^{235}_{92}$U, and assume fission of all of the nuclei. How much energy would be released? Now reduce this amount to any percentage efficiency that you think might be practical. Estimate how much coal or gasoline it would take to produce the same amount of energy? (Hint: What is the order of magnitude for energy involvement in chemical reactions?) [7.35 x $10^{10}$ J, 10$^3$ kg]

18. How much energy would be released by complete conversion of one mole of deuterium to helium? The reaction is $^2_1$H + $^2_1$H = $^3_2$He + $^1_0$n. [5.14 x $10^{11}$ J]

19. The heat from the sun at the earth’s surface is 1.35 kilowatts per square meter, and the distance between the sun and the earth is 1.5 x $10^8$ km. The mass of a hydrogen atom is 1.08144 amu and that of a helium atom is 4.00387 amu. Assume that the source of the solar energy is a process in which four hydrogen atoms are converted into one helium atom. How much hydrogen is used up per second? [3.18 x $10^{17}$ hydrogen atoms per second]

20. If a uranium-235 power plant has a conversion efficiency of 16 percent, and the average release per fission of the uranium-235 is 180 MeV, how much uranium would it take to produce 1 gigawatt hour (one million kWh) of electrical energy? [7.85 x $10^{23}$ atoms of uranium or 0.30 kg of uranium-235]

21. Compare fission and fusion as potential energy sources for the future.

22. Nuclear radiation has effectively been used to measure the thickness of metallic sheets. Outline a procedure that might be used for this purpose.

23. Using the value of 200 MeV as the energy released in one $^{235}_{92}$U fission, find the TNT equivalent for a 1 kg of $^{235}_{92}$U if one ton of TNT releases 10$^9$ cal of energy. [1.96 x $10^4$ tons of TNT]