CHAPTER 22

IONIZING RADIATION

22-1 INTRODUCTION

On March 28, 1979, an accident sequence took place at the Three Mile Island Unit 2 nuclear power facility. Widespread media attention, investigations, and a presidential commission (the Kemeny Commission) focused the attention of the nation on this event for a long time. The commission report cited many contributing factors, including operator error, lack of training, complexity of the failure, lack of information to operators, and design deficiencies in the control room. In addition, there was a bureaucratic snarl that withheld information about a similar malfunction at another plant. Among the materials released were 15 Ci of iodine (^{131}I).

On April 26, 1986, the nuclear power plant at Chernobyl, in the northern Ukraine region of the Soviet Union, exploded. Several people were killed and more than 100,000 people were evacuated. More radioactive iodine and cesium was released from this accident than from all nuclear bombs and atmospheric testing since 1945. Airborne radioactive iodine and cesium contaminated large portions of Europe. The explosion produced much international public discussion about resulting dangers from low-level exposures, cleanup costs, and responsibilities across national borders. By 2000, funding from many parts of the world started a clean up of the remaining plant.

During October and November of 1988, national attention focused through the news media on the safety of Department of Energy nuclear plants used to produce weapons for national defense. Reports addressed the dangers to workers (past and present) and surrounding communities at Fernald, Ohio, Hanford, Washington, and other locations. Government officials acknowledged the release of 230 tons of radioactive materials into the air and water at the Fernald plant and the release of 530,000 Ci of ^{131}I at Hanford between 1944 and 1957. One of the key issues in this discussion was the need to replace aging facilities and the multibillion dollar cost to the nation. With the end of the Cold War, projects began to clean up these plants.

Ionizing radiation draws a great deal of emotional response from the public. There are many factors contributing to this response, including fears related to the devastation of the atomic bombs dropped in World War II and fears of cancer and other health effects. There are economic issues, concern for terrorism, liability limits, long-term dangers of some isotopes, lack of understanding about ionizing radiation, and many other aspects that contribute to the opinions and beliefs expressed in the public debate. The complex issues confound the safety aspects of ionizing radiation. Public attention and discussion continues on such issues as low- and high-level waste disposal and decommissioning nuclear facilities after their useful life is over.

Safety and Health for Engineers, Second Edition, by Roger L. Brauer

The purpose of this chapter is to explore the hazards of and controls for ionizing radiation, not to address the many issues this topic involves. However, readers should perform an evaluation of this complex subject and, as best they can, separate the emotional elements involved in written material before forming their own opinions.

22-2 PHYSICS OF RADIATION

Ionizing radiation is any electromagnetic or particulate radiation capable of producing ions when it interacts with atoms and molecules.

Types of Radiation

The main types of radiation are x-rays, gamma rays, alpha particles, beta particles, neutrons, and other high-energy particles.

Alpha particles have the same structure as the nuclei of helium atoms: two protons and two neutrons. Relative to other forms of ionizing radiation, alpha particles are large. They have little penetrating power and are stopped by a piece of paper or the outer layer of skin.

A beta particle is an electron (negative charge) or positron (positive charge) separated from the nucleus of an atom. Smaller than alpha particles, beta particles travel at higher speeds and have enough penetrating power to pass through nearly $^1/_4$ in of tissue.

Gamma radiation is not a particle; it is energy waves in the electromagnetic spectrum. During radioactive decay, certain materials emit gamma rays from the nucleus of decaying atoms. Gamma rays have much greater penetrating power than beta particles and are best stopped by dense materials.

X-rays are similar to gamma rays. They are energy waves generated from outside the nucleus of an atom during decay or by impact from external electrons. X-rays have penetrating powers similar to gamma rays.

Neutrons are particles that have high mass and no charge. They are not produced spontaneously; they are produced by nuclear reactions. Neutron energies are classified as slow, medium, and fast. Because neutrons readily penetrate matter, high-density materials containing high levels of hydrogen atoms are necessary to stop them.

Sources of Radiation

There are two main sources of ionizing radiation: natural and artificial. Natural radiation sources include cosmic and gamma radiation found in certain soils. Building products made from these radioactive soils also give off natural radiation. These sources create external exposures. Natural radiation also is present in some ingested food and water and some inhaled air. These are internal exposures. Estimates indicate that people in the United States receive approximately 125 mrem of natural radiation per year: 100 mrem externally and 25 mrem internally. Natural exposures vary considerably by geographic location.

Artificial sources that expose the general population are certain consumer products, medical sources, occupational sources, and general environment sources. Products with ionizing radiation include television sets, computer monitors, some smoke detectors, luminous dials on clocks, and luminous signs. Medical sources are gamma rays, beta rays, and x-rays for diagnostic and treatment procedures. Occupational sources involve jobs related to manufacturing of products with radiation sources, medical services and research, mining, production of radioisotopes, nuclear fuel and weapons, transportation, and waste handling. There are both exposures during normal job functions and exposures during accidental releases.

Units of Measure

There are several kinds of measures related to ionizing radiation: measures for physical characteristics, for biological effects, and for converting physical measures to units of biological effects. There are also measures that express the amount of ionizing radiation absorbed by an exposed person.

Physical The energy levels of ionizing radiation are measured in megaelectron volts (MeV). Units of measure of ionized air are roentgens (R), and a curie (Ci) is the amount of radioactive material that has a disintegration rate of 3.7×10^{10} atoms/s.

Radioactivity decays with time. The time required for a material to lose half of its activity is its half-life. Half-life values are found in tables of physical properties of radioactive materials.

Radiation Dose The amount of radiation absorbed by the body per unit of tissue mass is the rad (radiation absorbed dose). The dose corresponding to the absorption of 100 erg/g of tissue is 1 rad. A millirad (mrad) is one thousandth of a rad. Absorption may occur over the whole body or in local tissue.

Biological Effects Radiation produces biological effects on the human body. Different types of radiation produce effects at different rates. Rems (roentgen equivalent man) are units of biological effect. The effect produced by a dose of 1 R of x-rays is 1 rem. Different types of radiation are absorbed at different rates. As a result, different doses are needed for different materials to produce similar biological effects. The relative biological effect (RBE) is the measure of biological effect (rem) divided by the dose (rad). Table 22-1 lists doses necessary for equivalent biological effects.

22-3 HAZARDS

Exposure to radiation may produce a variety of effects in humans. Damage is a function of the type of radiation, dose, the tissue and organs exposed, and age. In general, radiation affects rapidly developing cells most, which makes radiation therapy useful for rapidly growing cancer cells. It also makes radiation more dangerous for infants and children who have many rapidly developing cells.

Some organs concentrate materials. For example, iodine concentrates in the thyroid gland. Physicians have treated hyperthyroidism with radioactive iodine, which, when con-

TABLE 22-1 Dose Equivalents for 1 rem of Radiation

Dose (rad)	Type of Radiation
1	1 R of gamma rays or x-rays
1	x-rays, gamma rays, or beta particle radiation
0.1	Neutrons and high-energy protons
0.05	Particles heavier than protons and with sufficient energy to reach the lens of the eye

centrated by the thyroid, destroys cells. Another example is concentration of strontium 90 (^{90}Sr) by mammary glands. Cows that consume food contaminated with ^{90}Sr produce highly contaminated milk. ^{90}Sr has a fairly long half-life and becomes a more persistent contaminant than other radioactive materials, such as ^{131}I, which has a short half-life. High-dose rates are usually acute exposures. Their effects include ulceration of skin and intestinal tissue and reductions in white cell production. Symptoms of acute radiation sickness are weakness, sleepiness, and eventually stupor, tremors, convulsions, and death. Symptoms may include nausea, vomiting and diarrhea, loss of hair, and bleeding. Death may occur after 1 or 2 days or may be delayed up to several weeks.

Low-dose rates may be acute or chronic. Effects of low-dose rates often are delayed. There may be damage to cell structure and function and cells may die. Low levels may produce reddening of skin or damage to internal organs. Ionizing radiation may produce genetic effects, leukemia and other cancers, cataracts, and reduction in life span. Statistical studies of populations form the basis for knowledge of low-level effects.

For whole-body radiation, the most critical organs and tissues are the lens of the eye, the blood-forming organs (red bone marrow), and the gonads. Internal radiation sources may affect several vital organs.

Linearity Hypothesis

High-dose rates, on the order of 500 to 600 rems, are fatal to approximately half of an exposed population. At the other extreme, people receive low levels of radiation from natural and other sources throughout their lifetime. Statistical studies have compared effects of low-level exposures to the general population, but it is difficult to estimate the actual effect, particularly when the main concern is cancers that appear as much as 30 to 40 years after exposure. Consequently, the picture at the low end is unclear. For convenience in estimating effects, the linearity hypothesis extrapolates the effects at high levels to effects at low levels. The effects lessen at lower levels. The hypothesis suggests that the likelihood of dying of cancer increases with exposure. Experts do not agree on the use of the linearity theory and the effects from low-level exposures.

Studies of effects became more controversial in 198l, when there was a recalculation of data from the explosions at Hiroshima and Nagasaki. The recalculations suggested that cancers resulted from lower-energy gamma rays, whereas previous studies had suggested that high-energy level neutrons and protons were the primary forms of radiation. These data suggested that low-energy forms of radiation were more dangerous than previously thought.[1]

22-4 EXPOSURE STANDARDS

In general, standards for ionizing radiation assume that effects are cumulative. Therefore, exposure limits include a period of exposure. The limit can be exceeded by a single, acute exposure or by repeated exposures over an extended time. Several organizations have exposure standards. A few will be noted in succeeding text.

Table 22-2 gives a summary of exposure standards from selected federal agencies. Some agencies, such as the Tennessee Valley Authority (TVA) and the Department of the Navy, have adopted standards more stringent than some found in Table 22-2. There are additional standards for emissions from electronic products,[2] emissions from nuclear power plants,[3] and transportation, marking, and packaging of radioactive materials.[4]

TABLE 22-2 Exposure Limits for Ionizing Radiation

Exposure	Limit	Source
Whole body; head and trunk; active blood-forming organs, 1.25 rem per calendar quarter lens of eyes; gonads	1.25 rem per calendar quarter	OSHA[a], NRC[b]
Hands and forearms; feet and ankles	8.75 rem per calendar quarter	NRC[b]
	18.75 rem per calendar quarter	OSHA[a]
Skin of whole body	0.5 rem per calendar quarter	NRC[b]
	7.5 rem per calendar quarter	OSHA[a]
Individuals younger than 18 yr of age	1/10 of above limits	OSHA[a], NRC[b]
Drinking water: Radium (^{226}Ra and ^{228}Ra) and gross alpha particle	5 pCi/l	EPA[c]
Drinking water: gross alpha particle activity (excluding radon and uranium)	15 pCi/l	EPA[c]
Drinking water: beta particles and photons from artificial sources to total body or any internal organ	4 mrem/yr	EPA[c]
Air quality, exposure of the public		
Whole body	25 mrem/yr	EPA[d]
Critical organ	75 mrem/yr	EPA[e]
Average person	500 mrem/yr, 2 mrem/hr 100 mrem/7 days	NRC[f]
Nuclear industry worker	5(N–18) rem/yr, 3 rem/quarter	NRC[g]

[a] 29 CFR 1920.1096.

[b] 10 CFR 20.101: 1/10 for persons younger than 18 yr of age, 10 CFR 20.104.

[c] 40 CFR 141.15.

[d] 40 CFR 141.16; based on 2 l intakes per day for most radioactive materials.

[e] 40 CFR 61.102.

[f] 10 CFR 20.105.

[g] 10 CFR 20.101, where N is age in years at last birthday.

22-5 CONTROLS

There are several types of engineering controls to limit dangerous exposures to radiation: limiting radiation emissions at the source, limiting time of exposure, extending the distance from a source, and shielding. Other controls also help prevent dangerous exposures.

Limit Radiation Source

The best way to prevent radiation exposure is to limit the amount of radiation from a source. Limiting the quantity of ionizing material achieves this goal.

Time

Another method for minimizing risk to people is to limit the duration of exposure. One can prevent access to locations where radiation sources exist, which prevents unnecessary exposures. Procedures also can limit the duration of exposure. Because exposures are considered cumulative and because radiation cannot be sensed, one must use measurement and dosimetry. Measurement assesses quantity, whereas dosimetry incorporates the duration of exposure.

Radioactive materials decay with time. Each material has a radioactive half-life. A half-life is the time required for a material to decay to half of its original energy level. Because radioactive materials decay, the danger of a material decreases with time. This is particularly true for materials having relatively short half-lives.

Distance

Generally, airborne particulates and gases that are contaminated are diluted with increasing distance. Particulates that are large enough will settle out of the air. Thus, distance will reduce the likelihood of exposure to radioactive materials released from an operation.

Radiation levels decrease with the square of distance from the source, the inverse square law. As shown in Figure 22-1, a person at one unit of distance from a source has some level of radiation exposure. At double the distance, the amount of radiation will be one fourth that of the first location. The level of radiation, I_{r}, is

$$I_{\mathrm{r}} = \frac{1}{n_{\mathrm{d}}^2}, \qquad (22\text{-}1)$$

where n_{d} is the number of distance units relative to some reference location. Distance is an appropriate solution for certain kinds of exposures. For example, distance is helpful in reducing external exposures but of little value for internal exposures.

Example 22-1 A dental technician takes x-rays of patients' teeth. The control cord for the x-ray machine allows the technician to stand 5 ft away. If the control cord is lengthened and allows the technician to stand 15 ft away, what reduction in radiation level would result?

Applying Equation 22-1 and assuming the exposure level for the initial position to be unity, the radiation at the new location would be $I_{\mathrm{r}} = 1/(3)^2 = 1/9$ of that for the first position.

Shielding

Reducing radiation levels with shielding is another form of protection. Shielding effectiveness, the ability of a specific material to attenuate radiation, varies with different forms of radiation. For example, to some extent, air attenuates low-energy beta waves, but it has little effect for other forms of radiation. Also, hydrogen is an effective attenuation medium for low-energy level neutrons.

Attenuation properties of materials are measured in half-value thicknesses. One half-value thickness will cut the energy level of radiation arriving at the material to one half as it leaves the material after passing through it. The amount of radiation absorbed, R_{a}, and the amount transmitted, R_{t}, are given by

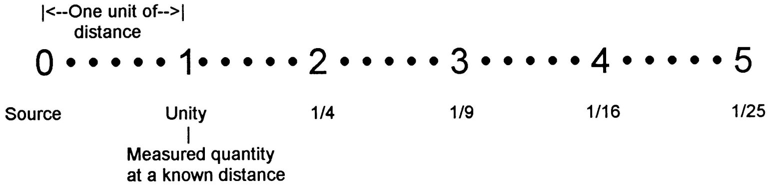

Figure 22-1. Radiation decreases with the square of the distance from a source.

$$R_a = R_0\left[1-\left(\frac{1}{2}\right)_n\right] \tag{22-2a}$$

and

$$R_t = R_0\left(\frac{1}{2}\right)_n, \tag{22-2b}$$

where

n is the number of half-value thicknesses and

R_0 is the amount of arriving radiation.

Published tables give attenuation properties of materials. Table 22-3 contains selected attenuation properties.

Example 22-2 One foot of water shields neutrons at 60 MeV. By what percent is the energy level of the neutrons reduced? What radiation level passes beyond the water shield?

From Table 22-3, the half-value thickness of water for neutrons is 9.25 cm. The number of half-value thicknesses is (1 ft × 30.48 cm/ft/9.25 = 3.295 half-value thicknesses. The attenuation of the shield is $1 - (1/2)^{3.295} = 1 - 0.102$ or 89.8% reduction. The radiation level leaving the shield is 60(0.102) = 6.11 MeV.

Barriers

Barriers can protect many radiation sources. For example, walls or fences around operations involving radiation sources will keep people out who should not be there. Liners under holding ponds of contaminated waste will prevent leaching into streams or groundwater.

Other Safeguards

There are many other methods that help prevent or reduce exposures to radiation sources. Warnings, a variety of procedures, security systems, training of personnel, and analyzing systems for potential failure modes are some methods. American National Standards Institute (ANSI) standards and government regulations provide detailed guidance for many of these safeguards.

TABLE 22-3 Radiation Absorption Properties of Selected Materials

Material	Radiation Type	Half-Value Thickness	Attenuation Coefficient
Concrete	^{137}Cs	1.9 in	
	^{60}Co	2.6 in	
	^{198}Au	1.6 in	
	^{192}Ir	1.7 in	
	^{226}Ra	2.7 in	
Lead	^{137}Cs	0.65 cm	
	^{60}Co	1.20 cm	
	^{198}Au	0.33 cm	
	^{192}Ir	0.60 cm	
	^{226}Ra	1.66 cm	
Steel	^{137}Cs	0.64 in	
	^{60}Co	0.82 in	
	^{192}Ir	0.50 in	
	^{226}Ra	0.88 in	
Water	Neutrons	9.25 cm	0.602/cm

Warnings Warnings should mark locations and equipment where there are ionizing radiation sources. Figure 22-2 shows the standard ionizing radiation symbol. Packaging and labeling of radioactive material requires this symbol as well. Visual warnings, such as flashing lights and audio signals, help people in an area recognize when there is a danger associated with radiation operations or material is present that could be dangerous.

Evacuation Should there be a significant release of radioactive material that endangers people in a facility or the public located outside a facility, it is important to lessen their chance of exposure. Nuclear Regulatory Commission (NRC) and other regulations require evacuation plans for accidental releases.

Security Should radioactive material get into the wrong hands, there is a danger of exposure to numerous unknowing people. This has happened with medical materials. It has happened with reprocessed irradiated metal, which was distributed as furniture components. The metal was discovered when it triggered radiation alarms during a delivery to a site that monitored all departing and entering vehicles and people.

Procedures play a major role in controlling entry or exit of radioactive material from sites. Typical procedures include security, physical monitoring and manifest systems. Security procedures and physical security systems also can prevent unauthorized persons from entering a facility or entering dangerous locations.

Dosimetry Because one cannot sense radioactive material, it is essential to monitor exposures of people who work with and around such material. Various measurement methods are described in Section 22-6.

Training People who work with and around radioactive material need training to understand the hazards of ionizing radiation. They need to understand how to protect themselves

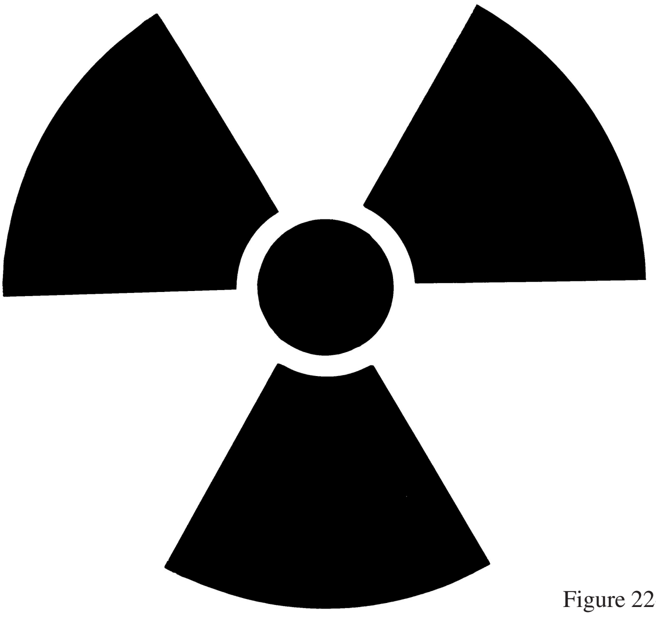

Figure 22-2. Standard radiation symbol.

and what procedures to follow. They need to develop skill in performing activities correctly and to know the value of protective clothing.

The public and people responsible for the public need training to deal with emergencies. If there are evacuation plans, police and other emergency organizations need to know what to do and need to have skill in completing assignments.

Complex systems involving radioactive materials often have a simulator, which allows trainers to create a variety of situations for teaching operators and others how to react, make judgments, and act correctly.

System Design and Analysis In operations and facilities involving radioactive material, there is seldom the luxury of waiting for things to go wrong. Analytical techniques, such as those described in Chapter 36, are useful for anticipating what might go wrong. A notable study of nuclear power plant failures[5] applied such methods. Although failures in such complex systems are difficult to predict and foresee, such methods are essential in ensuring safety.[6]

22-6 MEASUREMENT

Instruments

Instruments for measuring ionized radiation typically include a sensing device and a readout device. Some are useful for field measurement, whereas other combinations come in small packages useful for dosimetry. Sensors are most critical, because different types of sensors are appropriate for different types of radiation. Sensors include Geiger-Mueller tubes (used in Geiger counters), ionization chambers, luminescent detectors, scintillation detectors, and photographic emulsions.

A Geiger-Mueller tube is a gas-filled chamber used to measure alpha, beta, and gamma radiation. Radiation entering the tube ionizes the gas and creates small currents that the instrument measures.

Ionization chambers measure beta rays, gamma rays, and x-rays using a charge placed on an electrode in a tube. Radiation ionizes the air surrounding the electrode and allows charge to leak away. The amount of charge lost is related to the amount of radiation arriving at the chamber. Pocket ionization detectors are common dosimetry devices.

Luminescent detectors measure exposures to neutrons. Arriving radiation changes the energy content of solids in the detectors. The energy change causes them to emit light. The amount of light is proportional to the energy change.

In scintillation detectors, incoming radiation strikes a thin layer of crystals or a solution of organic materials that produce light. Light output is proportional to the radiation absorbed. These devices measure alpha, beta, gamma, and slow neutron sources.

Radiation-sensitive photographic film detects gamma rays and x-rays. The radiation affects the emulsion similar to the way light does. The developed films are compared with standards to establish the radiation exposure. Film badges are common dosimetry devices that use this method.

Surveys

OSHA and other agencies require surveying of areas that will be occupied to determine if they comply with regulations and standards for ionizing radiation. A survey may include background readings for radiation with follow-up readings at various times. It can also include analysis of operations and methods for each area of concern.

Dosimetry

One must monitor the exposure for each worker involved with ionizing radiation. Visitors' exposures are also important. OSHA and other organizations require such records. Typically, individuals wear film badges, pocket ionization detectors, or other instruments while in areas where exposures are possible. Exposures are recorded and the records of exposure are retained for each person.

22-7 RADON

Radon is a colorless, odorless, and radioactive gas that is formed from the complex decay of uranium. It is found naturally in many locations in soil, rock, and water and is often found in mining and ore tailings. The decay products of radon, called radon daughters, emit alpha, beta, and gamma radiation. Most have very short half-lives. In the late 1980s, radon gained much national attention, and programs to map the presence of radon in homes and buildings spread across the country. The concern resulted from recognition that radon gas can accumulate in houses and other buildings and the variety of decay products can be inhaled over extended periods. Concentrations may build within buildings to levels that are considered dangerous and could contribute to increased lung cancer rates.

Current standards recommend radon levels of 4 pCi/l or less. Methods to prevent buildup of radon concentrations include ventilating crawl spaces, foundation drain tile, and other locations. Assessment of construction sites for radon and control methods for radon are now an important element of facility design and real estate transactions.

22-8 IRRADIATED FOOD

A potentially useful application of radiation is in food preservation. Procedures for irradiating food to prevent spoilage and extend shelf life have been recognized for some time. The Food and Drug Administration has standards for the production, processing, handling, and packaging of food.[7] However, the public has been very reluctant to accept irradiated food products.

EXERCISES

1. A gamma radiation source, radium (^{226}Ra), is used in a hospital laboratory. If shielding is considered as a means of control, how many inches or centimeters are needed to reduce the radiation level to 1% of what a worker would be exposed to without shielding? Assume the shielding material is
   - **(a)** concrete
   - **(b)** steel
   - **(c)** lead
2. An alternative to Exercise 1 is to extend the distance between the radiation source and the worker. The initial design placed the worker 2 ft from the source. If a revised design placed the worker 10 ft from the source, what percent reduction in radiation exposure would there be for the second position relative to the first?

3. Another worker must reach into the instrument in Exercise 1 each day to make a calibration check. In so doing, the worker is exposed to some radiation. If only his hands and forearms are exposed and there are 60 working days per calendar quarter, how much radiation is the worker allowed to receive per work day to reach just the allowable limit in a quarter?
4. Visit a facility that uses radioactive material (power plant, laboratory, medical facility, etc.). Discuss with the staff what precautions they take in preparation for using a fissile source, during its use, and in disposing of used materials. Find out what contingency plans they have in place to deal with a release to the atmosphere or a loss of material by theft or other means.

REVIEW QUESTIONS

1. Name five kinds of radiation and characterize each.
2. Name two natural sources of radiation.
3. Name three products that produce or are sources of radiation.
4. Explain the following units of measure for radiation:
   - **(a)** MeV
   - **(b)** half-life
   - **(c)** rad
   - **(d)** roentgen
   - **(e)** rem
   - **(f)** RBE
5. What factors determine whether a radiation exposure is safe or harmful?
6. What effects may result from high dose rates of radiation?
7. What effects may result from low-dose rates of radiation?
8. What organs are most susceptible to damage from whole-body radiation exposure?
9. What is the linearity hypothesis?
10. What is a half-value thickness and for what means of control is it used?
11. List eight controls and safeguards that can reduce the exposure to or injury from radiation exposure.
12. Explain how each of the following works in measuring radiation:
    - **(a)** Geiger-Mueller tube
    - **(b)** ionization chamber
    - **(c)** luminescent detectors
    - **(d)** radiation sensitive photographic film
13. What is radon? Where is it found? How is it controlled?

NOTES

1 Marshall, E., "New A-Bomb Studies after Radiation Estimates," *Science*, 212:48–51 (1981).

2 21 CFR 1020.

3 40 CFR 190, 10 CFR 20.105, and 10 CFR 20.106.

4 49 CFR 172.

5 *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,* WASH-1400, U.S. Nuclear Regulatory Commission, U.S. Government Printing Office, Washington, DC, 1975. Available from National Technical Information Service, Springfield, VA.

6 H. W. Lewis, "The Safety of Fission Reactors," *Scientific American*, 242:3:53–65 (1980).

7 21 CFR 179.

BIBLIOGRAPHY

American National Standards Institute, New York:
There are numerous standards on safety in construction and operation of nuclear facilities, radiation protection, radiation instrumentation, and radioactive equipment. Readers should refer to a complete listing of ANSI standards and standards of the Nuclear Regulatory Commission (NRC), 10 CFR.

ATTIX, F. H., *Introduction to Radiological Physics and Radiation Dosimetry*, Wiley, New York, 1986.

BRODSKY, A., ed., *Handbook of Radiation Measurement and Protection*, CRC Press, Boca Raton, FL, 1980.

GUSEV, IGOR, GUSKOVA, ANGELINA, and METTLER, FRED A., eds, *Medical Management of Radiation Accidents*, 2nd ed., CRC Press, Boca Raton, FL, 2001.

HOPKE, P. K., ed., *Radon and Its Decay Product: Occurrence, Properties, and Health Effects*, American Chemical Society, Washington, DC, 1987.

KLEMENT, A. W., Jr., *Handbook of Environmental Radiation*, CRC Press, Boca Raton, FL, 1982.

LEWIS, E. E., *Nuclear Power Reactor Safety*, Wiley, New York, 1977.

MILLER, K. L., and WEIDNER, W. A., *Handbook of Management of Radiation Protection Programs*, CRC Press, Boca Raton, FL, 1986.

ORN, MICHAEL K., *Handbook of Engineering Control Methods for Occupational Radiation Protection*, Prentice Hall, Englewood Cliffs, NJ, 1992.

PROFIO, A. E., *Radiation Shielding and Dosimetry*, Wiley, New York, 1979.

SHAPIRO, J., *Radiation Protection,* Harvard University Press, Cambridge, MA, 1972.

STEWART, D. C., *Data for Radioactive Waste Management and Nuclear Applications*, Wiley, New York, 1985.

TOTH, L. M., MALINAUSKAS, K. P., EIDAM, G. R., and BURTON, H. M., eds., *The Three Mile Island Accident: Diagnosis and Prognosis,* American Chemical Society, Washington, DC, 1986.

WHICKER, F. W., *Radioecology: Nuclear Energy and the Environment*, 2 vols., CRC Press, Boca Raton, FL, 1982.