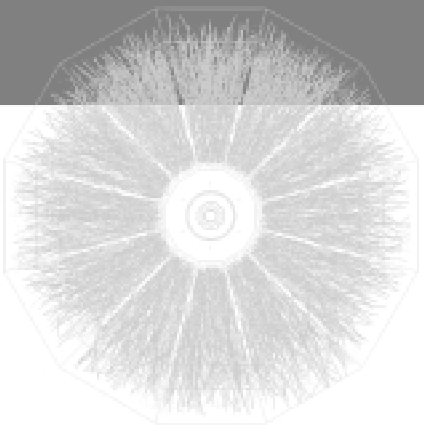

More

Radiation Dosage

The biological effects of radiation are principally due to the ionization it produces. Even a small amount of ionization can seriously disrupt the function of sensitive living cells or even kill them. Three different units are used to measure these effects: the roentgen, the rad, and the rem.

The *roentgen* (R) is defined as the amount of radiation that produces $(1/3) \times 10^{-9}$ C of electric charge (either positive ions or electrons) in 1 cm^3 of dry air at standard conditions. It is a measure of exposure to radiation. The roentgen has been largely replaced by the *rad* (*r*adiation *a*bsorbed *d*ose), a measure of the energy absorbed, which is defined as the amount of radiation that deposits 10^{-2} J/kg of energy in any material. The SI unit, joules per kilogram, is called a *gray* (Gy). Thus

$$1 \text{ rad} = 10^{-2} \text{ Gy} \qquad \textbf{12-36}$$

Since 1 R is equivalent to the deposit of about 8.7×10^{-3} J/kg of energy, the rad and the roentgen are of roughly equal magnitude. The amount of biological damage depends not only on the energy absorbed, which is equivalent to the number of ion pairs formed, but also on the spacing of the ion pairs. If the ion pairs are closely spaced, as in the ionization caused by α particles, the biological effects are increased. The unit *rem* (*r*oentgen *e*quivalent in *m*an) is the dose that has the same biological

TABLE 12-5 Approximate RBE factors

Type of radiation	RBE factor
Photons < 4 MeV	1
Photons > 4 MeV	0.7
β particles < 30 keV	1.7
β particles > 30 keV	1
Slow neutrons	4 or 5
Fast neutrons	10
Protons	10
α particles	10
Heavy ions	20

(*Continued*)

TABLE 12-6 Radiation and dose units

	Customary unit		SI unit		
Quantity	Name	Symbol	Name	Symbol	Conversion
Energy	electron volt	eV	joule	J	1 MeV $= 1.602 \times 10^{-13}$ J
Exposure	roentgen	R	coulomb/kilogram	C/kg	1 R $= 2.58 \times 10^{-4}$ C/kg
Absorbed dose	rad	rad or rd	gray	Gy = J/kg	1 rad $= 10^{-2}$ J/kg $= 10^{-2}$ Gy
Dose equivalent	rem	rem	sievert	Sv	1 rem $= 10^{-2}$ Sv
Activity	curie	Ci	becquerel	Bq = 1/s	1 Ci $= 3.7 \times 10^{10}$ decays/s $= 3.7 \times 10^{10}$ Bq

effect as 1 rad of β or γ radiation. One rem of any kind of radiation has about the same biological effect on a person:

$$\text{Dose in rem} = \text{RBE} \times \text{dose in rad} \qquad \textbf{12-37}$$

where RBE is the *r*elative *b*iological *e*ffectiveness factor. Table 12-5 gives approximate values of the RBE factors for different types of radiation. The SI unit for dose equivalent is the *sievert* (Sv), which is defined as the product of the gray and the RBE:

$$1\ \text{Sv} = 1\ \text{Gy} \times \text{RBE} = 100\ \text{rem} \qquad \textbf{12-38}$$

Table 12-6 compares the various radiation units we have discussed.

TABLE 12-7 Average radiation dose received by a member of the U.S. population[†]

Radiation source	Average effective dose (mSv/y)
Cosmic rays	0.27 (= 27 mrem/y)
Internal radioactive nuclides	0.39
Consumer products	0.10
Ground	0.28
Radon	2.0
Diagnostic x rays, nuclear medicine	0.53
Global fallout	0.01
Nuclear power	0.01

Source: National Council on Radiation Protection and Measurement (NCRP) Report 93, Washington, D.C., 1987.

(*Continued*)

Our knowledge of the effects of large radiation doses comes mainly from the studies of victims of atomic bomb explosions. Doses under 25 rem over the entire body seem to have no immediate effects. Doses of 50 to 100 rem damage the blood-forming tissues, and those of 500 rem usually lead to the death in a short time of 50 percent of those exposed. Exposures over 700 rem are invariably fatal.

The long-term effects of sublethal doses acquired over a period of time are more difficult to measure. The chances of dying of cancer are doubled by a dose somewhere between 100 and 500 rem. Not much is known about the effects of very low-level doses. It is possible that there is some threshold dose below which the damage done is repaired so that there is no resulting increase in the chance of cancer. But it is also possible that there is no threshold and that the cancer-causing effects of radiation are proportional to the cumulative dose even at low levels. This is the subject of active current research.

Some typical human radiation exposures are listed in Table 12-7. The internal dose listed in this table is from radioactive nuclei, such as ^{14}C, ^{40}K, and uranium and its decay products, inside our bodies. Most of the radioactive fallout due to nuclear weapons testing is ^{90}Sr and ^{137}Cs, both of which have half-lives of about 30 y. If there is no further testing, this source of radiation will eventually become negligible. We are shielded from most cosmic radiation by the atmosphere. The dose we now receive is about 40 mrem/y at sea level; it increases by about 1 mrem/y for every 30 m of altitude.

TABLE 12-8 Recommended dose limits

	Maximum permissible dose equivalent for occupational exposure
Combined whole-body occupational exposure	
Prospective annual limit	5 rems in any one year
Retrospective annual limit	10–15 rems in any one year
Long-term accumulation to age *N* years	$(N - 18) \times 5$ rems
Skin	15 rems in any one year
Hands	75 rems in any one year (25 per quarter)
Forearms	30 rems in any one year (10 per quarter)
Other organs, tissues, and organ systems	15 rems in any one year
Fertile women (with respect to fetus)	0.5 rem in gestation period
Dose limits for nonoccupationally exposed	(5 rems per quarter)
Population average	0.17 rem in any one year
An individual in the population	0.5 rem in any one year
Students	0.1 rem in any one year

Source: National Council on Radiation Protection and Measurement (NCRP) Report 93, Washington, D.C., 1987.

(*Continued*)

One of the decay products of the ^{238}U decay chain is ^{222}Rn, which decays by α emission with a half-life of 3.82 days. This decay is followed by other α and β decays that result in ^{210}Pb, which has a half-life of 22.3 y. Since radon is an inert gas, it diffuses through materials without interacting with them chemically. It is recognized as a health hazard because it seeps into buildings from the ground, where it accumulates, and enters the lungs during respiration. Should it decay while in the lungs, the energy deposited by its α particle and those of its decay products in the sensitive lung tissue can cause significant damage and can result in lung cancer. This constitutes the largest component of human exposure to natural sources of radioactivity.[12]

The largest source of artificial exposure to radiation is currently medical diagnostic x rays. The dose received varies enormously, depending on the type of machine used, the sensitivity of the film, and so forth. For a chest x ray, some mobile units give doses of 1000 millirems, and the average dose is around 200 millirems. If the best procedures are used, however, the dose from a chest x ray can be limited to 6 millirems.

Because of our lack of knowledge about the risks of radiation, we should clearly limit our exposure to it as much as possible. Table 12-8 lists some of the dose limits recommended by the National Council on Radiation Protection and Measurement.

PROBLEMS

1. Radium taken internally was once thought to have broad therapeutic powers. (It doesn't!) In a famous case that led to the development of exposure regulation, a 100-kg man consumed about 3.5×10^4 Bq (about 1 μCi) per day of ^{226}Ra for more than three years before he died. The α particle emitted by ^{226}Rn has an energy of 4.78 MeV. Assuming all the radium stayed in his body and ignoring the radioactivity of radium's decay products, compute the radiation dose he was receiving per hour (in sieverts) after taking the radium elixir for one year. How does this compare with the average hourly dose calculated from Table 12-7?

2. Using the data in Table 12-5, 0.5 Gy of x-ray dose is equivalent to how many grays of (*a*) fast neutrons, (*b*) α particles, and (*c*) heavy ions?

3. A single dose of 5.0 Sv would be fatal to approximately half of the people who receive it. How many grays will deliver this dose, if the radiation is (*a*) x rays, (*b*) γ rays, (*c*) low-energy β rays, and (*d*) fast neutrons?

4. The absorption of x rays in matter is described by Lambert's law

$$I = I_0 e^{-\mu x p}$$

where I is the intensity of a beam I_0 after passing through a thickness of a material whose density is ρ. The quantity μ, which is wavelength-dependent, is called the *mass absorption coefficient.* For 0.04-nm x rays, the mass absorption coefficient for iron is 0.375 cm^2/g. What fraction of a beam of 0.04-nm x rays will emerge undeflected after striking a sheet of iron (*a*) 0.5 cm, (*b*) 1.0 cm, (*c*) 2 cm, and (*d*) 4 cm thick? The density of iron is 7.87 g/cm^3.

5. The EPA standard for maximum indoor radon exposure is 4 pCi per liter of air. (*a*) If the lung capacity of a person is 3.5 liters, how many atoms of ^{222}Rn are in the lungs of a person in a room that has the maximum allowed amount of radon? (*b*) If the total energy absorbed in the lungs from the decay of one ^{222}Rn nucleus to ^{210}Pb is 20.3 MeV and the lungs have a mass of 2.0 kg, what dose rate in rems does a person who breathes nothing but contaminated air for 1 y receive? (*c*) Assuming that the risk of lung cancer in non-smokers is proportional to the dose in rems of the radiation received by the lungs, by what factor is the probability of lung cancer increased for this person, assuming a background dose of 150 mrem per year?

(*Continued*)

6. Beginning 12 days after the reactor accident at Chernobyl on April 26, 1986, and continuing for 8 days, individuals in a portion of Florida received radiation exposure above normal background resulting from an average concentration of ^{131}I in the air equal to 1.36 pCi/m^3. Obtain an expression for total exposure due to this isotope during the 8-day period and calculate the dose equivalent received by an average individual in the exposed population. What fraction of the annual recommended whole-body dose limit does this represent?