4 Radionuclides in the environment

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4.1 Introduction

This chapter describes the nature, sources, concentrations, exposures, measurement technologies for and effects of natural and artificial radionuclides in the environment. At higher concentrations of such nuclides they are known to be able to cause negative effects on plants and animals. Then they are considered to be an environmental pollution, and mitigating actions might be necessary. In the context of energy production, radionuclides can play different roles for fission and fusion technologies (in the normal operation of many facilities of their fuel cycles and during/after accidents), as well as in fossil fuel burning (e.g. in coal/oil, ash, technologically enriched natural radioactive material (TENORM)), and even in domestic energy conservation (e.g. leading to significantly increased indoor radon levels).

4.2 Radioactivity and radionuclides

4.2.1 Atoms and energy

The smallest unit of a chemical element is the neutral atom. It consists of a specified number of Z positively charged *protons*, Z negatively charged *electrons*, and N *neutrons* (uncharged). The protons and neutrons, called *nucleons*, are bound tightly in a tiny nucleus at the center of the atom. The surrounding space is occupied by the electrons in rapid motion, occupying most of the volume of the atom. Since the proton and neutron masses are some 1840 times that of the electron, more than 99 % of the atomic mass resides in the nucleus. The number Z of positive charges in the nucleus determines the chemical element, and the sum $A = Z + N$ is called the mass number of the atom. A *nuclide* is an atom with specified values of Z and A (or N). With $Z = 27$ and $A = 60$, for example, the nuclide is "cobalt-60", written ^{60}Co. Nuclides of an element (fixed Z) with different mass numbers A (or neutrons N) are called *isotopes*. The nuclides ^{60}Co and ^{59}Co are isotopes of cobalt, having 33 and 32 neutrons, respectively. More than 100 chemical elements and a total of 2700 different nuclides are known. Some are found in nature, while others are man-made.

A nuclide of a given type has a unique amount of energy stored in it, compared with its unassembled constituent protons, neutrons, and electrons. A c*hemical reaction*, such as combustion, can occur when atoms are brought together in such a way that their electronic structures are altered. The forces that bring this about cause either the consumption or release of energy. By comparison, alteration of the relatively massive structures in a *nuclear reaction* typically entails thousands of time more energy per atom than a chemical reaction. In both kinds of reaction, the change in energy E is associated with the conversion of an amount of mass m according to Einstein's formula, $E = mc^2$, where c is the speed of light.

A plot of the binding energy per nucleon of different nuclides shows a broad maximum at medium mass numbers (see Fig. 1.1 in Sect. 1.1). This fact leads to the possibility of exothermic reactions by *fusion* of the nuclei of light atoms (e.g. H, D, or T) or from the *fission* of heavy nuclei. The energy thus released is available for conversion into thermal, electrical, and other useful forms.

4.2.2 Transitions of atoms: radioactivity

Among the 2700 known nuclides, approximately 700 are stable; that is, they continue to exist without change in their present state. The others, in contrast, undergo spontaneous transitions in which they break up, releasing energy and emitting radiation. This phenomenon, called *radioactivity* or *radioactive decay*, was discovered by Henri Becquerel in 1896. Such nuclides are said to be radioactive and are referred to as *radionuclides*. Several modes of radioactive decay are found in nature, as described in the next section. Most radionuclides decay by one or another of these modes, although some can decay in more than one way. Often the nuclide that is left immediately after decay is also radioactive. In this case, the decay process continues. An entire serial chain of radioactive progeny can thus be formed, ending with the production of a stable nuclide.

As far as is known, radioactive decay is a completely random process, unaffected by temperature, pressure, or other physical and chemical influences. In a large sample of radionuclides of a given type, some will undergo transitions relatively soon, while others might remain unchanged for long times. The rate of decay of the sample is called the *activity*. It is expressed as the number of transitions per unit time, e.g. as s^{-1} or d^{-1}. The unit s^{-1} is given the special name bequerel (Bq). Activity is related quantitatively to the nuclide's half-life, which is defined as the average time for one half of the nuclides in a sample to decay. The probability distribution that describes the number of atoms that decay in any given length of time is the binomial distribution. When a sample is large and the time of observation is so short that the activity does not change appreciably, then the binomial distribution is approximated extremely well by the Poisson distribution, which is often more convenient to work with. The number dn of atoms that will decay in a short time dt is then proportional to the number of atoms $n(t)$ present and to the length of time dt. Denoting the constant of proportionality by λ (called the decay constant), one has $\mathrm{d}n = -\lambda n\,\mathrm{d}t$. It follows that the number of atoms, $n(t)$, that are undecayed at time t in a sample having n_0 atoms originally (at time $t = 0$) is $n(t) = n_0 \exp(-\lambda t)$. One thus arrives at the familiar exponential decay law for radioactivity. The decay constant can be interpreted as the probability per unit time for the transition of a given atom. In terms of the half-life, T, the decay constant is given by $\lambda = (\ln 2)/T$.

4.2.3 Radiation emitted in transitions

Four principal types of transitions are important for environmental radioactivity and the radionuclides relevant to energy production. The transitions can be described in terms of the radiation emitted.

(1) An *alpha particle* is identical to the nucleus of the ^{4}He nuclide, having two protons and two neutrons. It is emitted spontaneously from the nucleus of some heavy nuclides, typically at one or a few discrete energies in the range of several MeV. If Z is the atomic number and A is the atomic mass number of the original nuclide, then the residual nuclide following an alpha decay has atomic number $Z - 2$ and mass number $A - 4$. As with most radioactive transitions, alpha decay changes an atom of one chemical element into another.

(2) A *beta particle* is an electron (β^-) or positron (β^+) that is emitted from a nucleus. Beta particles are emitted with a continuum of energies, ranging from keV to several MeV. Because a beta particle has so little mass compared with a nucleon, this transition does not change the mass number of the nuclide. As a result, in β^- decay the atomic number of a nuclide is increased by one; with β^+ decay, the atomic number is decreased by one.

(3) A *gamma ray* is a massless, uncharged photon of energy that is emitted from an excited nucleus. There is no change in atomic number or atomic mass number in the transition, which therefore leaves the chemical element unchanged. Alpha and beta transitions frequently leave a residual nucleus in an excited energy state. The nucleus can then emit gamma photons, usually almost immediately, in order to shed the excess energy. Most alpha emitters also emit gamma radiation. Many beta emitters do also, although a number of radionuclides are pure beta emitters without gamma rays.

(4) *Neutrons* are emitted in a number of nuclear reactions and in the fission of a heavy nucleus. Fission of a ^{235}U nucleus releases almost 200 MeV of energy, which is some 30…40 times more than the energies associated with the foregoing three transition types. Splitting of the nucleus is accompanied by emission of several neutrons and gamma rays as well as highly radioactive, short-lived nuclides, and a bimodal distribution of nuclides of intermediate mass number. Long-lived radioactive fission products that get into the environment present a potential health hazard.

Alpha and beta particles are electrically charged. In traversing matter, their charge gives rise to forces that rapidly slow them down and limit their depth of penetration. As a general rule, alpha particles are not as penetrating as beta particles. Gamma rays and neutrons, on the other hand, are electrically neutral. Depending on their energy, they can usually penetrate matter to much greater depths than charged radiation.

Both the type of radiation emitted and the nature of the decay products are relevant for the assessment of natural and man-made radioactivity in the environment. They determine the methods for detection and measurement of the radiation as well as criteria for the estimation of doses to exposed individuals. Alpha particles, for example, have such a short range in matter that they cannot penetrate the protective layer of dead skin of the human body. Alpha emitters external to the body are not normally considered to present a radiological hazard. Of great concern, however, is the naturally occurring atmospheric noble gas, ^{222}Rn, which emits an alpha particle with a half-life of 3.8 d. This nuclide produces a serial chain of short-lived alpha- and beta-emitting radioisotopes of Po, Bi, and Pb with half-lives of less than half an hour. These readily attach to dust and other aerosols in ambient air, which can then be breathed and deposited in the lungs of persons. There alpha particles from the progeny can damage the sensitive living tissues with which they come into contact.

Another example of the relevance of knowing the radiation properties and the nature of the progeny atoms is afforded by the nuclide ^{137}Cs, which played an important role following the nuclear reactor accident at Chernobyl. This nuclide emits a beta particle with a half-life of 30 a. Outside the body in the environment, this transition presents little concern as a biological hazard. However, in 95 % of the beta transitions the progeny nuclide is the metastable nuclide ^{38m}Ba, which emits a 662 keV gamma photon with a half-life of 2.55 min. This penetrating radiation can lead to substantial human exposures.

4.2.4 General relevancy of radionuclides in the environment

The presence of radionuclides in the environment, the assessment of their concentrations and/or effects, and the administrative limitation of their concentrations can be of importance for several reasons:

(a) Radionuclides are primarily atoms which can chemically act through their own normal chemical properties and/or – after an alpha or beta decay – through that of their progeny. In this respect they behave principally similar to their non-radioactive sister isotopes of the same element. However, isotopic differences related to their radioactive nature are possible and of relevancy in environmental chemical processes, e.g. because short-lived radioisotopes or those having short-lived radioactive mother atoms cannot reach e.g. geochemical or biokinetic environmental equilibrium. This can be due e.g. because the recoil energy of the mother atom, received during particle emission, can remove it from its original microenvironment e.g. in soil or in a tissue. The chemical (e.g. toxic) properties of radionuclides can be of larger practical concern than their property of radioactivity in particular for very long lived nuclides as is the case for the heavy metal uranium and for some transuranic elements.

(b) Radionuclides possess a characteristic “internal clock” (of the radioactive decay) and characteristic progeny products which can be used e.g. to determine transit times in environmental compartments, for the assessment of the local origin of a sample (e.g. of water in a river or ocean, or of an air parcel in the atmosphere) and of its time of release, as well as for age determination of a sample (e.g. of ceramics). Here sometimes the original initial concentrations or concentration ratios to other isotopes have to be known or estimated.

(c) Radionuclides can often be experimentally identified and their concentrations measured very sensitively and with high precision, in particular if they have half lives appropriate for the process under investigation and for the measurement times.
(d) Radionuclides emit ionizing radiation and, thus, can act and interact over long distances. Whereas the chemical action of a stabile isotope usually is confined to molecular dimensions of a nanometer or less, radionuclides emitting alpha particles reach other objects up to distances of several ten micrometers (in material of density 1 g/cm^3), beta particles reach up to several millimeters, and energetic gamma rays or neutrons easily up to several decimeters; in air these ranges are thousand times larger. This particular property of radionuclides can be exemplified by two isotopes of the element cesium: a stabile cesium isotope in a piece of surface soil can affect only another soil or plant molecule in direct atomic contact with it, whereas its radioactive "brother" ^{137}Cs located next to it can interact through the 662 keV gamma ray emitted during the decay of its very short-lived progeny ^{137m}Ba with the DNA in a human being standing on this soil hundred meters away and cause there damages of potentially serious biological concern.

It is often this latter, health-related property of the emitted ionizing radiation why these radioactive nuclides as well as materials containing them (e.g. waste repositories) or facilities using and/or emitting them (e.g. nuclear reactors) attrack attention of scientists, regulators, the media and of the public.

4.3 Natural radionuclides in the environment

It is likely that almost all stabile and radioactive isotopes known today in the environment were produced in cosmic processes very long times ago. In the mean time billions of years passed by, and most of the radioactive isotopes have practically disappeared because of their half lives being short compared to such long geological periods of time. This is true e.g. for the natural ^{241}Pu decay chain. Out of the 2000 radionuclides known today about 80 occur naturally in measurable concentrations in the environment. They come from this primordial origin, are due to continuous new production by cosmic sources or from anthropogenic actions.

4.3.1 Cosmogenic isotopes

The universe is densely permeated by ionizing radiation of various types (mainly protons, 85 %, and He ions, 12 %), with a wide span of energies and of different origins, e.g. from the sun (solar particle radiation) or from several galactic sources (stellar flares, supernova explosions, pulsar acceleration, explosion of galactic bodies). These cosmic rays interact with the earth (mainly with the atmosphere) and produce permanently about 15 types of radionuclides. From the atmosphere they find their ways also into other compartments of the environment including humans. Most of these cosmogenic radionuclides with half-lives above 1 d are listed in Table 4.1 with their characteristic properties and annual source strengths. The production rate of most of these radionuclides is highest in the upper stratosphere, depends on the geographic lattitude and is modulated with the 11-year solar cycle by its influence on the earth magnetic field.

All cosmogenic radionuclides have much shorter half-lives and represent only a much smaller fraction of the isotopes of an element (typically 10^{-7} and below) than primordial radionuclides (see below). The input of such cosmogenic radionuclides into soil and plants from the atmosphere occurs mainly by dry and wet deposition (e.g. for ^{3}H and ^{7}Be) or by photo-assimilation into plant material (e.g. for $^{14}CO_2$).

Table 4.1. Cosmogenic radionuclides, their production rates [99UNS], and decay characteristics [83ICR].

Radio-nuclide	Production rate [PBq/a]	Global inventary [PBq]	Half-life	Decay mode	Progeny nuclide
^{3}H	72	1275	12.33 a	ß$^-$	^{3}He
^{7}Be	1960	413	53.29 d	ec	^{7}Li
^{10}Be	64×10^{-6}	230	1.51 Ma	ß$^-$	^{10}B
^{14}C	1.54	12750	5.73 ka	ß$^-$	^{14}N
^{22}Na	0.12	0.44	2.6 a	ec	^{22}Ne
^{26}Al	1×10^{-6}	0.71	0.74 Ma	ec	^{26}Mg
^{32}Si	870×10^{-6}	0.82	172 a	ß$^-$	^{32}P
^{32}P	73	4.1	14.26 d	ß$^-$	^{32}S
^{33}P	35	3.5	25.34 d	ß$^-$	^{33}S
^{35}S	21	7.1	87.51 d	ß$^-$	^{35}Cl
^{36}Cl	13×10^{-6}	5.6	301 ka	ec (1.9 %) ß$^-$ (98.1 %)	^{36}S ^{36}Ar
^{37}Ar	31	4.2	35.04	ec	^{37}Cl
^{39}Ar	0.074	28.6	269 a	ß$^-$	^{39}K
^{81}Kr	0.017×10^{-6}	0.005	229 ka	ec	^{81}Br

4.3.2 Primordial isotopes

Atoms produced during the cosmic nucleosynthesis many billions of years ago are older than the earth (to which they condensed by gravitational forces) and called primordial nuclides or isotopes. About 45 of the 80 radionuclides occurring naturally in the environment in measurable quantities (see Table 4.2; here only the initial atoms of the decay chains are given) belong to the three decay chains of the long-lived mother atoms ^{232}Th, ^{235}U, and ^{238}U (Tables 4.3 to 4.5). The fourth natural decay chain has become extinct in the mean time because of the short half-life of its mother atom ^{241}Pu; however, there are again ^{241}Pu atoms in the environment from artificial sources like atomic bomb tests and nuclear energy production.

Such natural decay chains have typically 10 members which are sequentially produced over long time periods by radioactive decays of their respective interim predecessors (i.e. they are “radiogene” isotopes) until they all finally end up as stabile isotopes of the element lead (^{206}Pb, ^{207}Pb, ^{208}Pb). In addition, there are ca. 6 other primordial radionuclides, e.g. ^{40}K (which is naturally present e.g. in humans in mass activity concentrations of ca. 60 Bq/kg) and ^{87}Rb, which change into a stabile progeny atom already in one single step.

The concentrations of natural, primordial radionuclides in the human environment can be modified by human actions, and this to an extend which can lead to high radiological concern. Depending on the type of action this is described by either the expression “natural radiation exposure modified/enhanced by human practices” or “technological enrichment of naturally occurring radioactive materials” (abbr.: NORM or TENORM).

A classical example of the first action is the increase of natural radon levels (and those of its progenies) in human breathing air by living in houses instead of outdoors: this behavior restricts the atmospheric dilution to safe outdoor levels (ca. 5 Bq/m^3) of radon diffusing from the soil (with soil air radon concentrations of typically above 10000 Bq/m^3). The resulting radon concentrations within houses range from some ten (normal) up to several thousand Bq/m^3 (requiring serious, even costly mitigation). The indoor mean value of radon is (e.g. in Germany: 50 Bq/m^3) typically ten times its outdoor mean value. Another, similar example for this type of human modification of its radioactive environment is working in poorly ventilated mines or in caves (and thus in increased Rn levels). Also flying in airplanes as crew or passenger at higher altitudes increases significantly the normal human exposure to cosmic radiation

[99UNS, 00UNS]; professional transatlantic-flight aircrew members, therefore, have now been recognized as the group with the highest average occupational radiation exposure.

A typical example for the technological enhancement of primordial radionuclides are the increased concentrations of U and Th and its decay products in coal ash after fossil energy generation, in petroleum industry, and in solid deposits in pipes used for crude oil pumping from underground oil production [02IAE].

As examples of natural radionuclides in the environment the mean concentrations of natural potassium, ^{238}U, and ^{232}Th are given in Table 4.6.

Table 4.2. Primordial radionuclides, their decay characteristics, and natural concentrations in soils [83ICR, 99UNS].

Radio-nuclide	Fraction of element [%]	Half-life [10^9 a]	Decay mode	Progeny nuclide	Concentr. in soil [Bq/kg] median (range)
^{40}K	0.012	1.28	ec (10.7 %) ß$^-$ (89 %)	^{40}Ar ^{40}Ca	400 (140…850)
^{87}Rb	27.8	47.5	ß$^-$	^{87}Sr	ca. 7
^{138}La	0.09	105	ec (66 %) ß$^-$ (34 %)	^{138}Ba ^{138}Ce	
^{147}Sm	15	106	α	^{143}Nd	
^{176}Lu	2.6	37.8	ß$^-$	^{176}Hf	
^{187}Re	62.6	46	ß$^-$	^{187}Os	
^{232}Th	100	14	α, ß$^-$ chain	^{208}Pb	30 (11…64)
^{235}U	0.72	0.7	α, ß$^-$ chain	^{207}Pb	ca. 2
^{238}U	99.28	4.47	α, ß$^-$ chain	^{206}Pb	37 (16…110)

Table 4.3. Primordial decay chain of ^{232}Th [83ICR], and the nuclide-specific photon dose rates at 1 m height above homogeneously contaminated soil [94ICR].

Radionuclide	Half-life	Main decay mode	Dose rate [nGy/h per Bq/kg in soil]
^{232}Th	14 Ga	α	4.78×10^{-5}
^{228}Ra	5.75 a	ß$^-$	5.45×10^{-5}
^{228}Ac	6.15 h	ß$^-$	2.21×10^{-1}
^{228}Th	1.91 a	α	3.44×10^{-4}
^{224}Ra	3.66 d	α	2.14×10^{-3}
^{220}Rn	55.6 s	α	1.73×10^{-4}
^{216}Po	145 ms	α	
^{212}Pb	10.64 h	ß$^-$	2.77×10^{-2}
^{212}Bi	60.5 min	α (36 %), ß$^-$ (64 %)	2.72×10^{-2}
^{212}Po	0.3 µs	α	
^{208}Tl	3.05 min	ß$^-$	3.26×10^{-1}
^{208}Pb	∞	stabile	
		Sum in radioactive equilibrium:	6.04×10^{-1}

Table 4.4. Primordial decay chain of ^{235}U [83ICR].

Radionuclide	Half-life	Main decay mode
^{235}U	704 Ma	α
^{231}Th	25.5 h	ß$^-$
^{231}Pa	32.76 ka	α
^{227}Ac	21.8 a	α (1.4 %), ß$^-$ (98.6 %)
^{227}Th	18.7 d	α
^{223}Fr	22 min	ß$^-$
^{223}Ra	11.4 d	α
^{219}Ra	4 s	α
^{215}Po	1.8 ms	α
^{211}Po	36.1 min	ß$^-$
^{211}Bi	2.14 min	α (99.7 %), ß$^-$ (0.3 %)
^{207}Tl	4.77 min	ß$^-$
^{207}Pb	∞	stabile

Table 4.5. Primordial decay chain of ^{238}U [83ICR], and the nuclide-specific photon dose rates at 1 m height above homogeneously contaminated soil [94ICR].

Radionuclide	Half-life	Main decay mode	Dose rate [nGy/h per Bq/kg in soil]
^{238}U	4.47 Ga	α (99.9 %)	4.33×10^{-5}
^{234}Th	24.1 d	ß$^-$	9.47×10^{-4}
^{234m}Pa	1.17 min	ß$^-$	3.00×10^{-3}
^{234}U	245 ka	α (99.7 %)	5.14×10^{-5}
^{230}Th	75.4 ka	α	6.90×10^{-5}
^{226}Ra	1.6 ka	α (100 %)	1.25×10^{-3}
^{222}Rn	3.8 d	α	8.78×10^{-5}
^{218}Po	3.1 min	α (99.98 %), ß$^-$ (0.02 %)	
^{214}Pb	26.8 min	ß$^-$	5.46×10^{-2}
^{214}Bi	19.9 min	α (0.02 %), ß$^-$ (99.98 %)	4.01×10^{-1}
^{214}Po	164 µs	α	
$^{210}T1$	1.3 min	ß$^-$	1.15×10^{-4}
^{210}Pb	22.3 a	ß$^-$	
^{210}Bi	5.01 d	ß$^-$	2.07×10^{-4}
^{210}Po	138.4 d	α	
^{206}Pb	∞	stabile	
		Sum in radioactive equilibrium:	4.62×10^{-1}

Table 4.6. Photon dose rates at 1 m height above soil homogeneously contaminated with K_{nat}, ^{232}Th, and ^{238}U at different activity concentrations [96Kem].

Radio-nuclide	Specific activity [Bq/kg per ppm]	Mean concentration		Dose rate [nGy/h]		
		[ppm]	[Bq/kg]	per Bq/kg	per ppm	at mean concentr.[a])
K_{nat}	0.03117	16800	523	0.0414	0.00129	22
^{232}Th	4.1	10.3	42	0.623	2.6	27
^{238}U	12.4	3.2	40	0.461	5.8	19

[a]) Including contributions of progeny nuclides in radioactive equilibrium.

4.3.3 Technical radionuclides in the environment

Mankind has produced and released into the environment a large array and large quantities of different technical radionuclides. Some were produced (or concentrated) to serve a particular purpose, some were just unwanted waste products, others were released in accidents. Many of them result from facilities connected to energy production. However, it should be clearly mentioned that the worldwide concentrations of radionuclides are dominated by naturally occurring nuclides and their modifications by human practices or by technology. Only locally occur artificial radionuclides e.g. from atomic bomb testing and from accidents (or mismanagement) of nuclear facilities in concentrations high enough to cause serious radiological concerns.

4.3.3.1 Nuclear fuel cycles

The nuclear energy fuel cycle (see Chapts. 1 and 3) comprises many different facilities needed (i) to mine for uranium in deep shafts or large open pits, (ii) to mill the raw ore to extract U_3O_8 ("yellow cake"), (iii) to purify and convert it to gaseous UF_6, (iv) to enrich the concentration of the atom ^{235}U in the natural uranium isotope mixture from 0.7 % to levels of typically ca. 3 % needed technically for controllable self sustained fission chain reactions in the reactor, (v) to fabricate pellets of sintered UO_2 powder and put them into Zircaloy tubes representing the nuclear fuel elements for the (vi) nuclear reactor. After usage for energy production and after subsequent time periods of "cooling" for the decay of short-lived fission products, the used fuel might be (vii) treated in a reprocessing plant to reclaim e.g. unused ^{235}U or newly formed fissionable ^{239}Pu, or brought directly to the (viii) waste treatment and disposal facility, e.g. deep underground, from where initially (i) the uranium originated, and, thus, closing the cycle.

Each of these 8 stages has its characteristic spectrum and quantities of radionuclides (and of several other factors of potential environmental or human impact) released into the environment (primarily into the atmosphere or into surface or underground water bodies) in normal operations and of those potentially emitted in incidental or accidental situations. These radionuclides – with greatly different environmental and biological behavior and importance – can belong to the natural uranium decay chains of the fuel material, e.g. uranium isotopes, ^{226}Ra, ^{222}Rn and its progeny; they can be fission fragments, e.g. (with thermal neutron fission fragment yield of ^{235}U in percent, radioactive half-life) ^{3}H (0.01, 12.3 a), ^{85}Kr (0.29, 10 a), ^{89}Sr (4.79, 51 d), ^{90}Sr (5.77, 28 a), ^{91}Y (5.4, 58 d), ^{137}Cs (6.15, 30 a), ^{129}I (0.9, 17 Ma), ^{131}I (3.1, 8.1 d), ^{144}Ce (6.0, 285 d), ^{103}Ru (3.0, 40 d), ^{106}Ru (0.38, 1.0 a), ^{95}Zr (6.2, 65 d), ^{140}Ba (6.32, 12.8 d), ^{143}Ce (5.7, 33 h), ^{147}Nd (2.7, 11 d); or neutron activation products of reactor or fuel materials, e.g. (with radioactive half-life) ^{3}H (12.3 a), ^{14}C (5568 a), ^{24}Na (15 h), ^{32}P (14 d), ^{35}S (87 d), ^{41}Ar (110 min), ^{45}Ca (164 d), ^{54}Mn (291 d), ^{55}Fe (2.6 a), ^{59}Fe (45 d), ^{57}Co (71 d), ^{58}Co (71 d), ^{60}Co (5.2 a), ^{65}Zn (245 d), ^{239}Pu (24360 a), ^{239}Np (2.3 d), ^{241}Am (470 a), ^{242}Cm (163 d).

4.3.3.2 Fossil fuel

The extraction and processing of earth materials (e.g. combustion of coal, other energy production from fossil fuel, use of phosphate rock, as well as mining and milling of mineral sands) can lead to modified exposures of humans and the environment to natural radionuclides. However, this hazard from radiation is generally small compared to that from the chemical substances involved. The world production of coal was about 3.4×10^9 t in 2000. A large fraction is burned in electric power stations with about 3×10^6 t needed to produce 1 GW a of electrical energy. With average radionuclide concentrations in coal of 50, 20, 20 Bq/kg of ^{40}K, ^{238}U, and ^{232}Th this leads to significant amounts of natural radionuclides being involved in form of coal and fuel ash even in non-nuclear energy production. The resulting collective effective dose for the world population per year of practice has been estimated by UNSCEAR to be of the order of 8000 man Sv [93UNS]. The large quantities of bottom and fly ash produced (about 280 mill. t per year) are used in a large variety of applications, the largest being the production of cement, concrete, road stabilizer, road fill, asphalt mix, and fertilizer. About 5 % is even used for the construction of dwellings. Alone the annual use of fly ash for the latter purpose has been estimated to lead to human collective doses of the inhabitants of such dwellings of about 50000 man Sv [93UNS]. Here, only the external irradiation is considered; the radon noble gas released could add significant inhalation doses.

The usage of other fossil fuels such as oil, peat, and natural gas for energy production, traffic, etc. has been estimated to lead to much smaller radiation exposures. However, it might be interesting to consider the amounts of radon involved in natural gas heating: The annual worldwide production and burning of about 10^{12} m^3 of gas with a typical radon concentration of 1 kBq/m^3 leads to a nominal annual radon emission through the chimneys of about 1000 TBq [93UNS]. Also, geothermal energy can be a significant source of radon: from measurements in Italy and the USA UNSCEAR estimated the average discharge of radon per unit geothermal energy production to be 150 TBq per GW a (leading to an annual collective effective dose of about 2 man Sv).

However, all these releases and exposures are relatively small as compared to the overall exposure of humans and the environment from the other natural sources of radiation mentioned above.

4.4 Major radioactive releases

Over the past six decades there were many major routine or accidental releases of radionuclides into the environment from nuclear weapons production and tests, from peaceful power production, and from the use of isotope sources (Tables 4.7 and 4.8). Following the first US nuclear test explosion and the atomic bombing of the cities of Hiroshima and Nagasaki in 1945, the USA and the USSR began production and testing of nuclear weapons in the atmosphere, on the ground surface, underwater, and underground. These tests led to sometimes high local contaminations, but most of the radionuclide inventory was released into the stratosphere from where it is still being deposited in the environment, mainly in the northern hemisphere. Subsequently, in the 1950s peaceful nuclear power production and reprocessing was developed, and in 2001 nuclear reactors were operated in 31 countries. Radionuclides are used in industry, medicine and science in many countries around the world. Large releases of radionuclides have taken place mainly in the 1950s and 60s because of the nuclear arms race (with particularly high yield detonations in 1957/8 and 1961/2), nuclear energy imperfections, and underestimations of the dangers of radiation.

The releases of concern were in particular in the form of nuclear fission and neutron activation products with half-lives above one year: ^{3}H, ^{14}C, ^{90}Sr, ^{137}Cs, Pu isotopes, and ^{241}Am.

After deposition in the biosphere the isotopes of Sr, Cs, Pu, and Am remain rather local. The soft beta-ray emitters ^{3}H and ^{14}C, however, are important isotopes in the environment, can travel long distances in their volatile forms of H_2O and CO_2, respectively, and become globally dispersed before their decaying.

The reactor accident of Chernobyl, Ukraine, on April 26, 1986, led to a prolonged atmospheric release (about 10 days) of large quantities of radionuclides, and to significant health, economic, environmental, social and political consequences, and countermeasures in many countries affected. The specific features of this accident (explosion and fire) favored a widespread distribution of radioactivity throughout the northern hemisphere, but the highest contaminations were found in countries of the immediate neighbor-

hood. Tables 4.9 and 4.10 give impressions of the long-range atmospheric transport observed in this accident (the deposited activities of radionuclides stated were measured near Munich, i.e. at a distance of ca. 1500 km from the source), of the complexity of the radionuclide spectral source term expected to be released in a reactor accident (with time dependencies being different for different nuclide groups), and of their time-dependent radioactive decay products (Table 4.10). The tables indicate also the complexity of the exposure pathways to humans caused by the radionuclide concentrations in air, soil, water, and short- and long-lived biosphere which must be quantified with the help of dose conversion coefficients (indicated there as well): external exposure from the soil or small contaminated objects, internal exposures from inhalation (including resuspended aerosol particles), and ingestion of contaminated food; the relative importance of these exposure pathways varies considerably as a function of time after the accident.

The largest doses were received on site by about 600 emergency workers during the night of the accident, with 93 having estimated whole-body exposures above 2.1 Gy (up to 16 Gy) and subsequently suffering from severe acute radiation sicknesses (up to death). More than 116000 persons of the general population were evacuated within the first few weeks after the accident from the most contaminated areas of Ukraine and Belarus [00UNS]. The large release of ^{131}I led to significant thyroid doses in large regional populations, mainly through the air-grass-cow-milk pathway. As a consequence, with a few years latency the incidence of thyroid tumors increased substantially in particular among persons who had been of younger ages at the time of the accident. Doses to organs and tissues other than the thyroid were much smaller on average. Therefore and because of the short follow-up period since 1986, in 2004 there appears to be no epidemiological evidence yet of any other increased cancer risk than of the thyroid among the general regional population.

Table 4.7. Major accidental and routine releases of radioactivity into the environment [97Bal].

Activity	Mode of release	
	Routine	Accidental
Military purposes		
Weapons production	Hanford, USA (1944-51) Chelyabinsk, USSR (1948-56)	Techa River, USSR (1949-51) Kystim, USSR (1957) Windscale, UK (1957) Rocky Flats, USA (1969) Tomsk-7, USSR (1993)
Atmospheric tests	Nevada, USA (1951-62) Semipalatinsk, USSR (1949-62) Novaya Zemlya, USSR (1955-62)	Altay, USSR (1949) Marshall Islands, USA (1954)
Nuclear fleet	Kola Peninsula, USSR	Chazhma, USSR (1985)
Weapons transport		Palomares, Spain (1966) Thule, Greenland (1968)
Power production		
Reactor operation	Worldwide	Three Mile Island, USA (1979) Chernobyl, USSR (1986)
Fuel processing	Sellafield, UK La Hague, France	
Radioisotope use		
Loss of sources		Cuidad Juarez, Mexico (1982) Goiania, Brazil (1987)
Satellite reentry		SNAP-9A, global (1964) Cosmos-954, Canada (1978)

Table 4.8. Amounts of nuclide-specific radioactivity released (in PBq) [97Bal].

Event	^{131}I	^{137}Cs	^{90}Sr	^{106}Ru	^{144}Ce	$^{239,240}Pu$
Techa river		12	12	10…20	ca. 10	
Nuclear tests 1952-62	6.5×10^5	910	600	12000	30000	11
Kystim		0.03	2	1.4	24	
Windscale	0.7	0.02		0.003		
Chernobyl	1200	85	8	30	140	0.07
Goiania		0.05				
Tomsk-7				0.01	0.0002	6×10^{-6}

Table 4.9. Artificial radionuclide deposition in Munich after the 1986 Chernobyl reactor accident, and the nuclide-specific external dose conversion coefficients for such point and area sources, as well as their ingestion and inhalation dose conversion coefficients. Columns 1 to 4 contain the nuclide characteristics; col. 5 gives the measured deposition [87Hoe, 86GSF] during the early period from April 29, 1986, 9:00 a.m. to May 2, 9:00 a.m. (reference time regarding radioactive decay corrections: April 30, 15:00); col. 6 gives the measured deposition for the longer period from April 20, 9:00, to June 2, 11:00 (reference time: May 6, 12:00 a.m.); col. 7 shows the dose rate coefficients for point sources (in µSv/h per GBq at 1 m distance) [92Tsc, 85Deb] for these nuclides; col. 8 shows the dose rate coefficients for radiation from the soil without/with consideration of progeny nuclides (after 50 years continuous deposition) [91Pet]; cols. 9 and 10 contain the dose conversion coefficients for the lower large intestine of an adult (a typical inner organ) in the most hazardous chemical forms [95ICR, 96EUR, 97ICR].

Nuclide	Half-life	Progeny nuclide	Half-life	Dep. Act. 1	Dep. Act. 2	Point DF	Soil w/o	Ingestion DF	Inhalation DF
				[kBq/m^2]		[µSv m^2/h GBq]		[nSv/Bq]	
^{54}Mn	312.5 d	^{54}Cr	stabile	0.029	0.03	130	2664	2.2/2.3	1.3/1.0
^{55}Fe	2.7 a	^{55}Mn	stabile	0.012	0.013	0	2×10^{-2}	0.1/0.36	0.17/0.25
^{89}Sr	50.5 d	^{89}Y	stabile	2.2		0	0	29/29	14/7.5
^{90}Sr	29.12 a	^{90}Y	64 h	0.2		0	0	26/26	20/12
^{95}Zr	63.98 d	^{95}Nb	35.15 d	0.4	0.4	112	2376/4680	7.8/7.8	4.2/2.4
^{95}Nb	35.15 d	^{95}Mo	stabile	0.5	0.5	121	2450	4.0/4.0	1.9/1.0
^{99}Mo	66 h	^{99}Tc (88 %)	2×10^5 a	9.3	2.1	38	470/790	3.1/3.3	5.5/3.1
		^{99m}Tc (12 %)	6.02 h						
^{103}Ru	39.28 d	^{103}Rh	stabile	24	24	81	1500/1500	6.5/6.6	3.1/1.7
^{106}Ru	368.2 d	^{106}Rh	29.9 s	6	6.4	34	—/650	71/71	37/2.1
^{110m}Ag	245 d	^{110}Ag (1 %)	24.6 s	0.4	0.44	408	8640/8640	11/11	5.9/5.7
		^{110}Cd (99 %)	stabile						
^{125}Sb	2.77 a	^{125m}Te (23 %)	58 d	0.8	0.9	—	1330/1330	5.8/6.2	3.3/2.0
		^{125}Te (77 %)	stabile						
^{127}Sb	3.85 d	^{127m}Te (18 %)	109 d	2.7	0.9	—	2200/2200	20/18	7.4/4.3
		^{127}Te (82 %)	9.35 h						
^{129m}Te	33.6d	^{129}Te (65 %)	69.5 m	27	26	12	101/216	25/23	11/5.6
		^{129}I (35 %)	1.6×10^7 a						
^{129}I	1.6×10^7 a	^{129}Xe	stabile	< 0.01		17	27	0.13/0.43	0.08/0.14

(continued)

Table 4.9 continued.

Nuclide	Half-life	Progeny nuclide	Half-life	Dep. Act. 1 [kBq/m^2]	Dep. Act. 2 [kBq/m^2]	Point DF [μSv m^2/h GBq]	Soil w/o [μSv m^2/h GBq]	Ingestion DF [nSv/Bq]	Inhalation DF [nSv/Bq]
^{131}I	8.04 d	^{131m}Xe (1 %)	11.9 d	85	53	59	1220/1220	0.04/0.16	0.025/0.033
		^{131}Xe (99 %)	stabile						
^{132}Te	78.2h	^{132}I	2.3 h	122	39	—	650/7920	3.8/19	1.6/4.3
^{133}I	20.8 h	^{133m}Xe (3 %)	2.19 d	3.7	(0.03)	99	1940/2050	0.039/0.13	0.021/0.025
		^{133}Xe (97 %)	5.24 d						
^{134}Cs	2.1 a	^{134}Ba	stabile	9.9	11.1	249	5040	22/22	14/7.8
^{136}Cs	13.1 d	^{136}Ba	stabile	3.9	3.2	336	6840	3.4/3.7	2.1/1.3
^{137}Cs	30 a	^{137m}Ba (95 %)	2.55 m	17.4	19.7	—/88	—/1800	14/17	9.1/5.2
		^{137}Ba (5 %)	stabile						
^{140}Ba	12.74 d	^{140}La	40.27 h	11	9.1	35/396	576/7560	26/29	4.3/9.2
^{140}La	40.27 h	^{140}Ce	stabile	7.8	10	325	6840	17/17	5.5/3.7
^{141}Ce	32.5 d	^{141}Pr	stabile	0.6	0.57	15	216	8.6/8.6	4.1/2.2
^{144}Ce	284.3 d	^{144m}Pr (2 %)	7.2 m	0.4	0.42	3.4	54/180	66/66	35/1.9
		^{144}Pr (98 %)	17.3 m						
^{234}U	2.4×10^5 a	^{230}Th	7.7×10^4 a	(ca. 3×10^{-5})					
^{237}U	6.75 d	^{237}Np	2.14×10^6 a	(ca. 0.026)					
^{238}U	4.5×10^9 a	^{235}Th	24.1 d	(ca. 3×10^{-5})					
^{239}Np	2.35 d	^{239}Pu	2.4×10^4 a	1.4	0.25				
^{238}Pu	87.7 a	^{234}U	2.4×10^5 a	(ca. 2×10^{-5})					
^{239}Pu	2.4×10^4 a	^{235}U	7.0×10^8 a	(both together:					
^{240}Pu	6537 a	^{236}U	2.3×10^7 a	ca. 5×10^{-5})					
^{242}Cm	162.8 d	^{238}Pu	87.7 a	(ca. 6×10^{-4})					

Table 4.10. Decay and exposure characteristics of the progeny nuclides of the artificial nuclides related to the Chernobyl reactor accident specified in Table 4.9. The column legend is the same as in Table 4.9.

Nuclide	Half-life	Progeny nuclide	Half-life	Point DF [μSv m^2/h GBq]	Soil w/o [μSv m^2/h GBq]	Ingestion DF [nSv/Bq]	Inhalation DF [nSv/Bq]
^{90}Y	64 h	^{90}Zr	stabile	—	—	31/	13/7.2
^{99m}Tc	6.02 h	^{99}Tc	2.1×10^5 a	22	369/360	0.025/0.03	5×10^{-3}/6×10^{-3}
^{99}Tc	2.1×10^5 a	^{99}Ru	stabile	—	—	1.1/3.2	0.57/1.1
^{106}Rh	29.9 s	^{106}Pd	stabile	34	650	6×10^{-6}/	1×10^{-6}/
^{110}Ag	24.6 s	^{110}Cd	stabile	5	97	8×10^{-7}/	6×10^{-7}/
^{125m}Te	58 d	^{125}Te	stabile		30	4.7/4.4	2.2/1.1
^{127}Te	109 d	^{127}I (2.4 %)	stabile		9/24	11/10	5.7/1.7
		^{127}Te (97.6 %)	9.35 h				
^{127}Te	9.3 h	^{127}I	stabile		15	1.3/1.1	0.23/0.24
^{129}Te	69.5 m	^{129}I	1.6×10^7 a		176/176	0.038/0.035	0.006/0.006

(continued)

Table 4.10 continued.

Nuclide	Half-life	Progeny nuclide	Half-life	Point DF [μSv m^2/h GBq]	Soil w/o	Ingestion DF [nSv/Bq]	Inhalation DF
^{131m}Xe	11.9 d	^{131}Xe	stabile	13	— (cloud)		
^{132}I	2.3 h	^{132}Xe	stabile	344	7200	0.028/0.038	0.011/0.011
^{133m}Xe	2.19 d	^{133}Xe	5.24 d	17	— (cloud)		
^{133}Xe	5.24 d	^{133}Cs	stabile	16	— (cloud)		
^{137m}Ba	2.55 m	^{137}Ba	stabile	98	1900	1×10^{-4}/	1×10^{-5}/
^{144m}Pr	7.2 m	^{144}Pr	17.3 min	5	22/148	7×10^{-4}/	
^{144}Pr	17.3 m	^{144}Nd	stabile	42	126	0.001/0.001	1×10^{-5}/1×10^{-4}
^{230}Th	7.7×10^4 a	^{226}Ra	1600 a		1/58	49/62	430/2400
^{237}Np	2.14×10^6 a	^{233}Pa	27 d	7	65/684	53/60	43/1300
^{234}Th	24.1 d	^{234}Pa	6.7 h		21/76	43/43	20/11
^{234}Pa	6.7 h	^{234}U	2.4×10^5 a		5400/5400	2.4/2.4	0.44/0.51
^{40}K	1.28×10^9 a	^{40}Ca (89 %)	stabile	21	576	5/19	3.2/6.5
		^{40}Ar (11 %)	stabile				
Th_{nat}		decay chain			3/5040	87/	1100/
U_{nat}		decay chain			11/47	48/	32/

4.5 Interactions of ionizing radiation with matter

4.5.1 Photons

A gamma-ray photon traversing a material interacts with individual atomic electrons and, to a lesser extent, with atomic nuclei. Electrically neutral, the photon will travel some distance before it randomly encounters one of these targets. In the *photoelectric effect*, the photon is absorbed by an electron and disappears completely in the interactioon. Its energy is transferred to the struck electron, which in turn deposits its energy and contributes to the dose in the vicinity of the collision site. Photoelectric absorption requires a minimum, or threshold, energy that the photon must have in order to extract the electrom from an atom. Alternatively, a photon can undergo *Compton scattering*. In this case, its path is deflected and only part of its energy is transferred to the struck electron. The photon then continues traveling with reduced energy in a different direction following the encounter. Photoelectric absorption is typically the dominant interaction for low-energy photons (less than about 100…150 keV) and materials of high atomic number. Compton scattering dominates at higher energies up to several MeV. At still higher energies, a photon can disappear in the production of an electron-positron pair. Pair production occurs in the field of an atomic nucleus or an electron. The probability increases with photon energy and with increasing atomic number of the medium.

Gamma photons can also participate in nuclear reactions. Usually, this probability is much smaller than that for the photoelectric effect, Compton scattering, or pair production. An example of a photonuclear reaction is provided by capture of a gamma photon by a ^{206}Pb nucleus followed by emission of a neutron from it. The reaction is written symbolically as ^{206}Pb(γ, n)^{205}Pb.

The transport of photons of a given energy in a homogeneous medium is characterized by an *attenuation coefficient* μ. Because the interaction occurs randomly, like radioactive decay, the relative number of photons that travel a distance x without having an encounter is exponential, $\exp(-\mu x)$. Analogous to the radioactive decay constant λ, the attenuation coefficient μ, which has the dimensions of inverse length, represents the probability per unit distance of travel that the photon will have an interaction. It can be expressed as the sum of the attenuation coefficients for the individual processes just described. The aver-

age distance of travel to a photon's first collision is $1/\mu$. Division of the attenuation coefficient by the density ρ of the medium provides the *mass attenuation coefficient* μ/ρ, which is the quantity most often tabulated.

4.5.2 Beta particles

Because it carries an electric charge, a beta particle (β^- or β^+) traversing a medium loses energy almost continually from the forces exerted on it by atomic electrons. The collision of a beta particle with an electron involves equal masses, and so the beta particle can be substantially deflected and can also lose a large fraction of its energy in a single encounter. As a result, beta particles travel through matter in tortuous paths. The distances that beta particles of a given initial energy travel before coming to rest in a material cover a broad distribution. The average of this distribution is designated as the *range* of a particle at that initial energy. Since the tracks are not straight, the average depth of penetration of beta particles into a target is less than the range, typically by a factor of about one-half.

With its small mass, a beta particle can also be deflected sharply by a nucleus, producing X-rays, called *bremsstrahlung*. The fraction of energy lost by this process increases rapidly with particle energy and with increasing atomic number of the medium.

The transport of beta particles at a given energy in a material is characterized by the average rate of energy loss per unit distance traveled. This quantity is called the *stopping power* of the material. It is often expressed in the units $\mathrm{MeV\,cm^{-1}}$. Dividing by the density ρ gives the *mass stopping power* of the material, e.g. in $\mathrm{MeV\,cm^2g^{-1}}$. The mass stopping powers of different media having similar atomic compositions are nearly equal. The total stopping power for beta particles is the sum of that due to collisions with the atomic electrons and that due to bremsstrahlung.

Like any charged particle, beta rays are slowed down almost continually in matter and will be stopped completely in a shield of sufficient thickness. Gamma rays, in contrast, keep traveling at the speed of light in a material until they have a random encounter. With their exponential attenuation, there is always a finite probability that a gamma photon will penetrate a shield of any thickness. For all practical purposes, thick gamma shields will reduce photon leakage to negligible levels.

4.5.3 Alpha particles

Like beta radiation, alpha particles are electrically charged and lose energy almost continually by collisions with atomic electrons as they traverse matter. Unlike beta particles, however, they travel in almost straight trajectories. Because the electrons with which they collide have a mass some 7500 times smaller, an alpha particle can lose only a small fraction of its energy and be deflected only slightly in a collision.

Compared with beta particles, alpha particles are "heavy" charged particles. Their stopping powers are typically several orders of magnitude larger than those for beta particles and their ranges are therefore much shorter. Unlike beta particles, most alpha particles of a given initial energy travel about the same distance when they stop in a material. Being a heavy charged particle, they are easy to shield. As mentioned above, alpha particles do not normally penetrate the dead layer of the skin. Also, alpha particles do not generate bremsstrahlung.

4.5.4 Neutrons

The uncharged neutron, like a gamma photon, travels without energy loss in matter until a random collision occurs. However, neutrons have no appreciable interaction with atomic electrons. They interact only via the so-called strong, or nuclear, force with atomic nuclei. The collision of a neutron witn a nucleus can be elastic, in which case the total kinetic energy of the neutron and struck nucleus is conserved – that is, unchanged by the collision. The nucleus recoils with an amount of energy equal to the energy lost by the neutron. On the other hand, the collision might be inelastic, in which instance some kinetic energy

disappears. The lost kinetic energy is spent in doing work against the forces that bind nucleons in the nucleus. Both kinds of interactions are important for neutron dosimetry.

Alpha, beta, and gamma rays transfer energy directly to the atomic electrons with which they collide in a material. The secondary electrons thus produced deposit energy and contribute to the dose (Sect. 4.5.5) in an irradiated medium. These are the initial events that can lead eventually to the production of biological damage. The mechanism is somewhat different for neutrons. The principal chemical constituents of soft tissue, which is about 80 % water, are, in order of atomic abundance, H, C, O, and N. "Fast" neutrons, having energies of about 100 keV or more, lose energy primarily by elastic collisions with the protons, which are the nuclei of the H atoms. The probability for these collisions is large, and the transfer of energy to the target proton of equal mass is the most efficient. The neutron can lose any amount of energy up to its total in a single elastic collision with H; on average, it loses one-half of its energy. As a heavy charged particle, the recoil proton does not travel far, and deposits its energy in the vicinity of the collision site. Elastic scattering of fast neutrons by the other atomic nuclei contributes considerably less to the dose.

Slow neutrons, by comparison, do not have large amounts of kinetic energy to convert into dose by the mechanism of elastic scattering. There are, however, two inelastic, exothermic nuclear reactions by which slow neutrons produce a tissue dose. In the first, the proton nucleus of the H atom captures a neutron with the release of a 2.22 MeV gamma photon, the reaction being written $^{1}H(n, \gamma)^{2}H$ (this reaction affords an example of the release of energy by the fusion of nucleons in light atoms). The surrounding tissue is exposed to the energetic gamma ray. In the second reaction, the slow neutron is captured by the nucleus of a nitrogen atom in the tissue with the ensuing reaction $^{14}N(n, p)^{14}C$. The energy released is 0.626 MeV, which is shared by the ejected proton and recoil ^{14}C nucleus and deposited locally at the capture site. The probabilities for neutron-capture reactions generally increase greatly with decreasing neutron energy.

4.5.5 Dosimetry

Dosimetry is the scientific undertaking that attempts to relate measurements of radiation fields to the chemical and biological changes that they might produce. In order to detect radiation and predict its consequences as well as to monitor and control the exposures of individuals, one needs a quantitative measure to describe the amount of radiation delivered. To this end, the *absorbed dose* in an irradiated target is defined as the amount of energy absorbed per unit mass. Its unit is the gray (Gy), defined as $1\ \mathrm{Gy} = 1\ \mathrm{J kg^{-1}}$ [98ICR].

To gain some perspective on the magnitude of the gray, Table 4.14 in Sect. 4.8 shows some of the symptoms expected as the result of a uniform, acute, whole-body exposure of a person to penetrating gamma rays. Individual responses would vary from person to person. No noticible symptoms are expected at doses less than about 0.25 Gy, although the higher exposures in this range are detectable in blood and other tissues. Doses above 0.25 Gy can lead to clinical changes in an individual with potentially serious consequences. Recovery should be possible at 3 Gy, but 6 Gy would likely be fatal. For comparison, consistent with ICRP recommendations, the annual exposure limit for an individual exposed to uniform, whole-body gamma radiation is 50 mGy = 0.05 Gy. Methods for measuring absorbed dose are described in Sect. 4.7.

In addition to absorbed dose, other concepts and quantities are needed in the assessment of personal radiation exposures. It is known that some kinds of radiation are considerably more effective than others in producing biological damage. Experiments have shown, for example, that a smaller dose of neutrons kills the same fraction of cells as are killed in a colony by a dose of X-rays. If the ratio of the doses is 10, for instance, one says that the *relative biological effectiveness* (*RBE*) of the neutrons for cell killing at that level is 10. Knowledge of the absorbed dose D_T received by an individual in an organ or tissue T is not, by itself, sufficient to assess biological damage. One also needs to know the kind of radiation R involved. For control purposes the ICRP specifies radiation weighting factors w_R for different radiations. Given the dose $D_{T,R}$ from radiation of type R, the *equivalent dose* to the organ or tissue T is defined as the product $H_{T,R} = w_R D_{T,R}$. Values of w_R range from 1 for gamma radiation to 20 for heavy charged particles. With $D_{T,R}$ expressed in Gy, the organ equivalent dose unit is the sievert (Sv). With a radiation weighting factor

$w_R = 10$, an absorbed dose of 1 μGy in an organ contributes an equivalent dose of 10 μSv to the organ. If the organ receives additional doses from other types of radiation R, then the total organ equivalent dose is the sum over R of the individual contributions, $H_T = \Sigma_R w_R D_{T,R}$.

It is also recognized that different tissues of the body have different sensitivities to radiation in producing damage in an exposed individual. The ICRP recommends a set of fractional tissue weighting factors w_T (whose sum over the whole body is unity) for the organs of the body. The *effective dose* for an exposed individual is the weighted sum of the organ equivalent doses, $E = \Sigma_T w_T H_T$, expressed also in Sv. This quantity is presumably a measure of the risk for stochastic effects to an individual in the context of long-term, low-level exposure to radiation. Stochastic effects, such as cancer, are those that occur randomly in a population. The frequency of the occurrence, but not the severity of the illness, increases with dose. For occupational radiation protection, the ICRP recommends an annual effective-dose limit of 50 mSv in order to limit the risk for stochastic effects. Radiation also produces deterministic effects, such as cataracts. The severity of such an effect in an individual increases with the dose, and there is usually a threshold dose below which the effect is not seen. To prevent deterministic effects in workers, the ICRP limits the annual equivalent dose to organs.

4.6 Radiation exposures from natural and artificial radiation sources

All living organisms and dead objects inthis world have always been naturally exposed to ionizing radiation. The sources of this radiation (cosmic rays, as well as terrestrial radionuclides occuring in the earth's crust, in air, water, food, in building materials, and in the human body itself) have been described in Sect. 4.3, and the resulting natural radiation exposures of the average population are given in Table 4.11. Some of the exposures are rather constant and uniform among individuals (e.g. from ingested ^{40}K), other exposures (e.g. U and Th in soil) can vary locally to a large extend. The building of and living in houses can strongly influence indoor levels of radon and its progeny which contribute significantly to inhalation doses.

Table 4.11. Radiation exposures from natural radiation sources.

Source of irradiation	Mean annual effective dose [mSv]			Typical range [mSv]
	External	Internal	Total	
Cosmic rays				0.3…1.0
directly ionizing component	0.3	—	0.3	
neutron component	0.055	—	0.055	
Cosmogenic radionuclides (^{3}H, ^{7}Be, ^{14}C,…)	—	0.015	0.015	
Primordial radionuclides				0.4…10
^{40}K	0.15	0.18	0.33	
^{87}Rb	—	0.006	0.006	
Uranium-238 series	0.1	1.24	1.34	
(where ^{238}U to ^{234}U	0.005			
^{230}Th	0.007			
^{226}Ra	0.007			
^{222}Rn to ^{214}Po	1.1			
^{210}Pb to ^{210}Po	0.12)			
Thorium-232 series	0.16	0.18	0.34	
(where ^{232}Th	0.003			
^{228}Ra to ^{224}Ra	0.013			
^{220}Rn to ^{208}Tl	0.16)			
Total	0.8	1.6	2.4	1…10

Another source of human radiation exposure is from medical uses of ionizing radiation in diagnosis and therapy. Because of large national variations in resources for medical radiology the national average exposures to these practices vary considerably. The average doses per caput in countries of different health care levels is given in Table 4.12. Here it should be mentioned that the numbers given represent only estimated values with large uncertainties and large individual variations.

There are many occupations (e.g. in medical clinics, nuclear installations, research centers) in which workers can be exposed to man-made sources of ionizing radiation. At the same or at other locations workers can also be exposed to enhanced levels of natural radiation due to human practices (see Table 4.13). In the occupational exposure area the data quality available is much better than in the medical field. The current UNSCEAR estimate of the worldwide collective effective dose to workers from man-made sources in the 1990s is about 2700 man Sv, which is by a factor of 2 lower than the corresponding value in the 1970s. A large contribution to this reduction comes from better radiation protection measures in facilities of the nuclear fuel cycle, in particular in uranium mining [00UNS].

As can be seen from a comparison of the exposure statistics for natural sources, in medicine and at the workplace by far the greatest contribution comes from natural background radiation. In addition, the possibly large local variation of indoor radon levels leads to significant variabilities of the natural radiation exposure.

Table 4.12. Radiation exposures from diagnostic medical X-ray examinations [00UNS].

Health care level	Population per physician	Annual examinations per 1000 people	Average annual effective dose per caput [mSv]
I	< 1000	920	1.2
II	1000…3000	150	0.14
III	3000…10000	20	0.02
IV	> 10000	< 20	< 0.02
Worldwide average		330	0.4

Table 4.13. Occupational radiation exposures [00UNS].

Source/Practice	Number of workers monitored (× 1000)	Average annual effective dose [mSv]
Man-made sources		
Nuclear fuel cycle (incl. U mining)	800	1.8
Industrial uses of radiation	700	0.5
Defense activities	420	0.2
Medical uses of radiation	2320	0.3
Education/Veterinary	360	0.1
Total from man-made sources	4600	0.6
Enhanced natural sources		
Air travel (crew)	250	3.0
Mining (other than coal)	760	2.7
Coal mining	3910	0.7
Mineral processing	300	1.0
Above-ground workplaces (Rn)	1250	4.8
Total from natural sources	6500	1.8

4.7 Radiation measurements

4.7.1 General methods

Ionizing radiation interacts with matter in a number of ways, which provide the bases for its detection and measurement. As its name implies, *ionization* is the formation of free electrons and charged atoms and molecular species, collectively called ions, in the matter traversed. An instrument with an external electric field can be made to collect the ions produced in a gas or semiconductor and thus provide from their number (under proper conditions) a measure of absorbed dose. Such an instrument can be made into a dose-rate meter by monitoring the rate at which ionization takes place. Ionization is both versatile and very sensitive. It can also be used to register ionization pulses from individual particles. The size of a pulse is proportional to the energy lost by the particle in the gas. Under the right conditions, the instrument operates as a proportional counter for measuring the energy spectrum of a radiation. With a very strong external electric field, any ionization event, no matter how small, in the gas will trigger a complete discharge through the gas. In this mode the detector operates as a Geiger counter. Radiation is easily detectable at levels far below those posing any significant danger to humans.

The use of radioactive materials in luminescent watch dials and instrument panels is familiar. *Scintillation* is another phenomenon utilized for radiation instruments. It is also the earliest detection method, in that scintillation provided the first evidence of the existence of ionizing radiation when noticed by Röntgen in the discovery of X-rays in November 1895. One of its principal uses is to measure the spectrum of energies of particles in a radiation field. Since the amount of light produced by the absorption of a particle gives a measure of its energy, scintillation proportional counting is used to measure energy spectra. Both organic and inorganic scintillators are available for radiation measurements.

Thermoluminescence dosimeters (TLDs) are worn as personnel monitoring badges for assessment of an individual's effective dose. The absorption of radiation by the TLD material (e.g. LiF) leaves electrons trapped in excited states. After the badge is worn for a period of time (e.g. 3 months), it is heated and "read" under controlled conditions. Heating drives out the trapped electrons, which thereby emit light. The reader and badge are calibrated to provide dose information from the light emitted. TLD dosimeters typically have several chips of sensitive material behind different absorbers. The combined readings from the different chips give information relevant to assessments of deep dose, beta skin dose, dose to the lens of the eye, and neutron exposures. TLDs are the most widely used personnel dosimeters today.

In earlier days, *film* was used extensively for personnel monitoring. The darkening in a set of films developed after exposure to known radiation doses was measured to calibrate the response of film badges worn by workers. Like TLDs, films are integrating dosimeters, rather than dose-rate meters.

A number of additional properties are employed for radiation detection and measurement. They are generally not as common as those mentioned here and will not be discussed.

4.7.2 Alpha particles

Because of the short ranges, an instrument must be placed in close proximity to an alpha source in order to detect the particles. Surfaces can be monitored for alpha contamination, for example, by using a flat, "pancake" probe having a ZnS scintillator covered by a thin Mylar window through which the radiation can pass. Light from the scintillator is collected and an electrical signal amplified by a photomultiplier tube is registered. Removable surface alpha contamination can also be monitored by taking "swipes", or "smears", of a surface with a piece of filter paper. The paper is then placed inside a gas-flow counter, where the alpha particles are emitted directly into the counter gas and registered. Monitoring for airborne activity from alpha as well as other types of radiation is common. Air is drawn through a filter to collect particulate material. The filter activity is then measured to provide an assessment of the average activity concentration in the sampled air. Air monitors can be fixed with alarms that activate when a preset level of activity is reached.

Alpha radiation from sources external to the body is not generally considered to be harmful to an individual. However, as mentioned already, alpha rays emitted internally are directly absorbed in living tissue and hence can present a serious potential health hazard. In many facilities, workers periodically submit urine samples for analysis for alpha emitters as well as other radionuclides. The samples are counted to obtain the rate at which activity is being excreted from the body. The measured excretion rate is used to infer the amount of activity in the body. Since the samples are analyzed in the presence of natural background radiation, special statistical protocols are often employed to interpret the measurements.

"Whole-body" counters are widely used to monitor some internally deposited radionuclides. Radiation detectors placed directly outside the body measure the energies of the gamma rays that are emitted internally and escape from the body. The observed values of the photon energies enable particular nuclides to be identified. The method can be applied to monitor alpha emitters if they also emit gamma rays. Because of their relatively low photon energies, whole-body counting for transuranic elements and the uranium series is frequently indistinguishable from natural background (e.g. from Compton-scattered photons emitted by natural radioactive ^{40}K in the body).

4.7.3 Beta particles

Survey instruments are available for air and area monitoring. Urinalysis programs and whole-body counting are carried out to assess internal beta emitters. Techniques for measuring beta radiation have much in common with those for alpha radiation. Two examples will illustrate some differences.

Tritium is an important and relatively hazardous radionuclide associated with nuclear energy. The isotope of hydrogen is a pure beta emitter, releasing low-energy particles with a maximum energy of only 18.6 keV. A tritium sample can be conveniently counted by dissolving and suspending it in a liquid scintillator. In this way the entire sample is registered in the detector.

In contrast to alpha radiation, external beta particles with energies above about 70 keV can penetrate the dead layer of the skin of the body. They present an external hazard. The particular organs of greatest concern from beta irradiation are the skin below the dead layer and the lens of the eye. For control purposes, calibrated TLD dosimeters are worn by workers to monitor these and other dosimetric quantities.

4.7.4 Photons

Gamma rays and neutrons are generally much more penetrating than charged particles. Ionization chambers are convenient for monitoring photons. Measurement of the current produced can be calibrated to furnish dose rate. Often the meters have a "thin window" that can be uncovered to allow beta radiation to enter and be detected as well as gamma. Geiger counters, also available with thin windows, are convenient and sensitive beta-gamma detectors. These instruments often have audible as well visible dial readouts.

Integrating pocket ion chambers are very useful. They are cylindrical condensers that are given a fixed charge in a reader at the beginning of work in a gamma field. At the end of the job they are placed back in the reader, which determines how much charge was lost because of ionization produced by the gamma radiation. Through calibration, this information provides a measure of absorbed dose. Some devices have an eye piece that allows reading the chamber at any time.

Gamma spectra can be measured with scintillation counters and with high-purity germanium (HPGe) solid-state detectors. The latter furnish high resolution between events that are close, but different, in average energy deposition. They are often useful for detecting the presence of one nuclide in the presence of another with overlapping signals.

Personnel monitoring for gamma radiation is accomplished as part of the common TLD dosimetry systems. They are usually calibrated to give the regulatory "deep" dose at a depth of 1 cm in tissue.

4.7.5 Neutrons

In order to measure neutrons, a detector must first present a nuclear target with which neutrons can interact, thus transferring or releasing energy in the material. Charged particles (electrons and recoil nuclei), gamma photons, and possibly other neutrons will be produced in the detector. Principles already described can then be applied to measure them. In almost any application in which neutrons are important, gamma radiation will also be present. Since the ICRP radiation weighting factors for the two radiations are different, the absorbed doses for the neutrons and gamma rays are needed separately in order to evaluate an individual's effective dose. Gamma discrimination is an important facet of neutron dosimetry. In addition, the radiation weighting factors are different of neutrons in different energy ranges. Therefore, knowledge of the neutron energy spectrum is also important for neutron dosimetry.

Fast neutrons can be monitored with a gas proportional counter. They interact primarily by elastic scattering to produce charged recoil nuclei in the counter gas. Because hydrogen is the most efficient element for reducing the energy of neutrons and because it is the most abundant element in soft tissue, the walls and gas of the counters are usually made of special tissue-equivalent materials. Under proper circumstances (i.e. Bragg-Gray conditions), the counters measure absorbed dose or absorbed dose rate. Gamma rays produce secondary electrons in the chamber. An electron typically produces much less ionization than a recoil nucleus that is struck by a neutron. Unless the gamma intensity is large, their relatively small pulses can be electronically excluded from registration, thus yielding an instrument with excellent gamma discrimination. Other gases, such as ^{3}He, are also used as proportional-counter gases for neutron measurements.

Neutron spectrometry, which is often difficult to perform, can be approached in several ways. In certain organic scintillators, fast neutrons produce recoil protons, which then generate pulses of light. Ideally, the amount of light in a pulse depends on the proton recoil energy, which in turn depends statistically on the energy that the incident neutron had. Practical complications in using this system arise from multiple neutron scattering of the incident neutrons and from nonlinearity of the light response.

Slow-neutron detectors rely on exothermic capture reactions by certain nuclei. The most important nuclides used for this purpose are ^{10}B, ^{6}Li, and ^{3}He. The compound BF_3 is a good proportional-counter gas, and chamber walls can also be lined with boron. Depending on the mode, slow-neutron capture by ^{10}B releases either 2.31 MeV (96 %) or 2.79 MeV (6 %) to the two recoil nuclei, ^{7}Li and ^{4}He. These large energy pulses following capture afford excellent gamma discrimination. Lithium is an important TLD material, and it can also be used as a scintillator. Both boron and lithium can be enriched above their natural abundances in the isotopes ^{10}B and ^{6}Li for increased neutron sensitivity. A ^{6}Li chip is included in some TLD badges to detect possible neutron exposure. Special TLD personal neutron monitoring badges are available.

Some instruments register fast neutrons by first slowing them down (moderation) in an appropriate material (e.g. paraffin) and then detecting them as slow neutrons by nuclear capture. The energy released provides good gamma discrimination. In addition, by using several detectors with moderators of different thicknesses, information about the neutron energies can be obtained. Spectral data can also be inferred from the radioactivity in materials having different energy thresholds for neutron reactions.

Bubble detectors are available to be worn as passive, integrating personal neutron dosimeters. The detector is a polymer that contains droplets of superheated liquid. Neutrons, striking the droplets, quickly lead to the formation of small gas bubbles. The bubbles are visible to the eye and remain fixed in the polymer. Their density depends on the neutron dose. After being worn, the bubble detector can be reset and reused. It does not respond to gamma radiation.

4.8 Biological radiation effects on humans

4.8.1 Acute and teratogenic radiation effects

Radiation exposure of humans can damage cells, causing death of some of them and modifying others (e.g. inducing mutations, transformations, DNA breaks, chromosome damage). Most organs and tissues of the human body are not affected by the loss of even a considerable number of cells. However, if this number is large enough, there will be considerable, observable harm to organs with symptoms of increasing severity that even, with increasing number of radiation-inactivated cells, can lead to death of the irradiated individual (Table 4.14). However, it should be noted that the values in this table hold for acute irradiations only: protraction of the dose delivery can increase these numbers considerably because of the strong dependency of the degree of cell activation on dose rate and of cellular repopulation.

Table 4.14. Possible effects of an acute whole-body exposure to penetrating gamma radiation.

Dose [Gy]	Symptoms	Remarks
0…0.25	None.	No clinically significant changes.
0.25…1.0	Mild prodromal symptoms such as nausea and anorexia might occur.	Bone-marrow, lymph-node, and spleen damage. Decrease in blood-cell, platelet, and lymphocyte counts.
1…3	Mild to severe nausea. Anorexia, malaise, and infection.	Severe hematologic damage. Recovery possible, but not certain.
3…6	Above effects pronounced. Infection, hemorrhaging, epilation, diarrhea.	Fatalities without treatment.
> 6	Above symptoms plus central nervous-system impairment.	Death expected.

Animal experiments and clinical experience have shown that the sensitivity of mammalian tissues and organs to irradiation is closely correlated with the degree of cell proliferation and differentiation. Therefore humans are particularly radiation sensitive during prenatal development. Irradiation during that time can lead to several types of effects: death of the embryo or fetus, induction of malformations, induction of growth retardation, induction of functional disturbances, and induction of cancer. The qualitative and quantitative extends of these effects depend on the developmental stage at the time of irradiation with significant differences, (a) in the preimplantation period (until about day 10 p.c.) characterized by rapid cell proliferation and differentiation, (b) the major organogenesis (lasting until the end of the second month p.c.) when various organs and tissues are formed, and (c) the fetal period (during the remainder of the pregnancy) when many growth and differentiation processes take place in all organs and tissues. It is assumed that irradiation (with doses of at least 0.25 Gy of low-LET (linear energy transfer) radiation) during the preimplantation period (a) will cause death in most cases [97Str]. During the phase of major organogenesis (b) mainly malformations can be induced at doses above about 100 mSv; the developing skeleton and CNS are especially sensitive. In mice and rats at doses of at least 200 mSv microcephalies, exencephalies and hydrocephalies have been observed [97Str]. After termination of major organogenesis, in phase (c), macroscopic teratogenic effects can no longer be induced and death becomes a major concern at higher doses. When the irradiation is fractionated or protracted during organogenesis the radiation effects are lower than after acute radiation exposures.

Acute and teratogenic radiation effects are sometimes specified as “deterministic” effects since a direct, “deterministic” correlation between radiation and induced effects can be established. For these types of radiation effects there exist dose thresholds, and they do not play any role at normal or slightly elevated environmental exposure conditions.

4.8.2 Stochastic late and genetic effects

Other human radiation damages may not have a dose threshold, e.g. modifications of the human genomic information might initially be possible even by one single radiation track. Although such damage is usually repaired, the repair may not be perfect and the resulting modification transmitted to progeny cells, and it may eventually lead to cancer, if one affected initial cell should actually be sufficient to start such complex processes. On the other hand, if the modified cells have the task to transmit hereditary information, the children of exposed humans may suffer from hereditary disorders [00UNS]. Since neither such radiogenic genetic disorders nor somatic cells in radiogenic tumors can be discriminated from those originating from "spontaneous", endogeneous processes, only stochastic statements on the likelihood of the cause of such a case can be made; therefore, these types of human radiation effects have been classified as "stochastic" radiation effects.

Damage to deoxyribonucleic acid (DNA) in the cellular nucleus is often considered to be the main initiating event by which ionizing radiation can cause long-term harm to human health. Damage to other cellular components (epigenetic changes), however, can also influence the functioning of a cell and lead to a malignant state. In addition, it might be possible that even by-standing cells (i.e. those not hit directly by a radiation track) can be affected (e.g. mutated or inactivated) by biochemical signals transmitted from cells having experienced direct radiation action. Cells have a large number of biochemical pathways recognizing and dealing with specific forms of damage to the DNA or with stress or for adaptation to other changed environmental conditions. They are designed to limit the extent of an initial stress. However, even if such protective processes are acting, misrepair of damage is possible giving the potential for cancer induction or hereditary disease. Unfortunately, the details of the multi-stage processes leading possibly to radiation-induced solid tumors, leukemias, or hereditary defects are still largely unknown and, thus, present estimations of human cancer and genetic risks must be based on observations in epidemiological studies (somatic risks) and on extrapolations from animal experiments (genetic risks).

Radiation-associated cancer risks are usually studied in population groups that have been exposed to doses large enough that the resulting cancer incidence is significantly in excess of the normal background rate. Statistically significant higher risks for radiogenic cancer were found e.g. in the most important radio-epidemiological study, the so-called "Life Span Study" (comprising 86572 exposed individuals of both genders of a broad age distribution) of the survivors of the atomic bomb explosions at Hiroshima and Nagasaki. However, they are seen only at organ doses above about 100 mSv [00UNS]. Epidemiology alone will not be able to resolve the important question whether much smaller doses are also carcinogenic in humans.

In the Life Span Study cancer incidence and mortality among the survivors have been observed since 1950; in 2000, 44 % of this group were still alive, and important data, especially for the groups of younger ages at the time of exposure, can be expected until, say, the year 2030. During the time period from 1950 to 1990 a total of 7578 deaths from solid tumors was observed among the survivors, of which about 334 were attributed to radiation exposure. During the same time period, 87 leukemia deaths of a total of 249 cases might have been due to the irradiation.

At doses above 100 mSv, statistically significant effects of radiation were found for cancers of the stomach, colon, liver, lung, breast, ovary, bladder, and thyroid, as well as for non-melanoma skin cancer. However, the total number of tumors is not sufficient to permit detailed analysis of the dose-response curves for many types of cancer; for all solid tumors lumped together a linear slope of about 10…13 %/Sv of this curve can be fitted to the data up to 3 Gy. This observation has strongly influenced the present "official" risk estimate for somatic radiation effects of 10 %/Sv after acute irradiation; for protracted and low doses of ionizing radiation a cancer risk factor half this value is assumed by the ICRP; genetic risks are assumed to be of the order of only 1 %/Sv. Statistically significant cancer risks were not observed in this study even at high doses for cancers of the rectum, gall bladder, pancreas, larynx, uterine cervix, uterine corpus, prostate gland, kidney or renal pelvis [00UNS]. Regarding leukemias, an association of radiation with most types was found, but not for CLL, lymphoma or multiple myeloma.

4.9 Biological radiation effects on biota

4.9.1 Historical development

The effects of natural radionuclides on plants have been investigated since the beginning of the 20th century. However, it was primarily the worldwide contamination with artificial nuclides by the atmospheric atomic bomb tests in the northern hemisphere since 1945 which raised concern about its environmental consequences. This, in turn, stimulated radiation ecological research into this topic for approximately 40 years and mainly in the USSR, the USA, Canada, France, Germany, UK, and Japan [61Bac, 61Woo, 82UNS]. After the Chernobyl reactor accident this area was weakly revived in Europe for about one decade. Here, also public and political movements in favor of better protection of the environment led to a general re-consideration of radiation effects on biota [92IAE], and even to the formation of a new committee dedicated to this field within the International Commission on Radiological Protection (ICRP) in 2003.

Historically most of the research on radiation effects on biota employed large field irradiation facilities (mainly with strong gamma-ray sources), observations in high natural background areas, at nuclear test sites, and in accidentally contaminated areas (e.g. Kystim, Urals), as well as the release of irradiated objects into the environment and experimental contamination of environmental objects, and/or observations of irradiated laboratory microcosms [82Whi]. While each approach has certain advantages, many suffer from a lack of either an adequately large irradiated area, sufficient dose or dose rate (in an environment contaminated with radionuclides, animals and plants would be irradiated internally and externally), or sufficient ecological realism (e.g. regarding the presence of other confounders, of appropriate microclimates, soil fertility, and competition from other species) for a sound extrapolation to conditions actually found in contaminated environments.

Although costs and other difficulties encountered when studying radiation effects on natural populations and communities have limited the possibilities to do research on a large number of species and types of communities, enough results could be obtained which permit an estimation of the likelihood that a given low-level radioactive environmental contamination will induce radiation effects observable at the population or community level. This holds true for ecosystems like deciduous or coniferous forests, for grassland and scrubland, herbaceous fields, agriculturally used fields, and moss-lichen communities; only little information, however, is available on artic, alpine, desert and tundra communities.

In specifying the types and amounts of relevant biological responses in irradiated ecosystems after high and low doses and dose rates of ionizing radiation several aspects must be observed. First, an operationally meaningful definition of “acute” or “chronic” irradiation is needed: in this context an “acute” exposure might be defined as one which is delivered in a time period which is short compared with times over which any obvious biological response develops; a “chronic” exposure might continue over a large fraction of the natural life of organisms under consideration [92IAE]. Second, a qualifier for the amount of total doses is needed: a “high” exposure leads to an acute response (usually a severe pathological reaction as e.g. mortality); a “low” exposure would lead only to marginal and late occurring effects on the normal biological life of an organism. It may produce detectable effects of certain biological processes of an organism but without any obvious harm to the individual. Third, in ecosystems maintenance of the populations will be the main concern of radiation protection (not protection of the individuum in human protection); it is influenced by effects on many attributes as e.g. mortality, fecundity, growth rate, vigor, and mutation rate, of an additional irradiation (but also by many other environmental factors other than radiation). Thus, the specification of radiation effects on biota is in many respects and in principle different from that concerning humans (Sect. 4.8).

4.9.2 Effects on plants

There are many types of radiation damages expressed in individual plants after high doses of ionizing radiation including mortality, reduced growth, reduction in tree crown condition (sprouting buds), production of pollen, or viability of seeds. On population or community level the indices usually determined include [92IAE, 74Whi]: the "coefficient of community" (CC) measuring the qualitative changes in species composition (i.e. the presence or absence of a species) after an irradiation in a plot considered, the "similarity index" (S) characterizing changes in the abundances of individuals within species, as well as in the number of species, the "diversity index" (H) which measures the balance among individuals of different species as well as the number of species, the "biomass index" (B) specifying the dry aboveground mass of biological tissue per unit ground area, and finally the "leaf fall index" (L) measuring the dry leaf mass deposited per unit of ground area.

Using these indices, Table 4.15 shows the observed minimum total gamma-ray exposures and the minimum exposure rates, respectively, that are needed to produce detectable effects in terrestrial plant communities. Many experiments have shown that pine trees are among the plants most sensitive to radiation. The deciduous trees (e.g. oaks), the shrubs, and the herbs show progressively less radiosensitivity, although within each plant group there are substantial variations. The sensitivities of cultivated plants, such as vegetables, grains, and fruit trees are similar to those of closely related species that occur in the wild [92IAE]. The radiation sensitivities appear to be predictable within a factor of two from the interphase chromosome volume. However, lichen-dominated communities are known to be exceptionally radioresistant, which might be due to the presence of diffuse centromers and the asexual mode of reproduction in addition to their small chromosome volumes [74Whi].

Table 4.15. Minimum gamma-ray exposures and exposure rates observed to produce detectable effects in terrestrial plant communities [92IAE].

Community type	Exposure period [d]	Attribute measured	Minimum exposure rate [Gy/d]	Minimum total exposure [Gy]
Pine forest	8	CC	3.75	3
Oak-pine forest	540	CC	0.5	270
	900	H	0.5	450
	1440	L	0.02	29
Deciduous forest	165	B	0.24	40
Tropical forest	34	B	1.18	40
Old fields	17	S, H	0.59	10
(abandoned cropland)	29	CC	12	350
	29	B, S, H	5.86	170
	365	CC	0.5	180
	365	H	1	360
Meadow vegetation	11	CC	2.27	25
Shortgrass plains	30	CC	4.67	140
	30	H, B	3	90
	420	CC	1.2	500
	420	H	0.4	950
	510	B	1.7	870
Lichen	92	S, B	22	2000
	780	CC, H	3	2340

It appears that the most radiation-sensitive plants in their natural environment show "acute" (better: short-term chronic exposure) radiation sensitivities of a magnitude similar to those found for mammals. Regarding long-term chronic irradiations it is considered very unlikely that at dose rates up to the order of 10 mGy/d any detrimental effect on plant communities would be observed.

4.9.3 Effects on animals

Radiation effects on mammals were studied mainly for two reasons. First, to obtain information on their own fate in their normal environment; second, in laboratory experiments as a surrogate model for predicting radiation responses of humans to various doses, dose rates and radiation qualities. After acute radiation exposures to gamma rays, $LD_{50/30}$ values (doses leading to lethality of 50 % of the exposed animals within 30 days) were observed in the range of 5…11 Gy, direct mortality of individual animals was found after acute whole-body doses down to 2 Gy. Significant work was also invested in studies of radiation effects on reproduction, and natality was recognized to be a more radiation-sensitive endpoint than mortality: minimal doses to depress reproduction might be as low as 10 % of the doses producing direct mortality: doses of 0.5 Gy, for example, produced measurable, transient changes in bull semen (with complete recovery after 30 weeks). The sensitivity of mammals to irradiation of the ovary varies greatly, with female mice being particularly sensitive: reproduction can be transiently impaired by doses as low as 0.2 Gy, with permanent sterility introduced by 1 Gy.

Although there are various factors that can modify the response of mammals to acute irradiation (e.g. hibernation, confinement, temperature, competition, etc.), it can be stated that such modifications are unlikely to contribute to mortality at acute whole-body doses below, say, 1 Gy. This holds true both for wild and domestic animals (the $LD_{50/30}$ for sheep, cattle, horses, and pigs after acute irradiation is in the range of 4…7 Gy). The dose rate, however, was found to be of large influence on lethality: e.g., at dose rates below 10 mGy/h the $LD_{50/30}$ of sheep increases to above 10 Gy.

The $LD_{50/30}$ values for birds were found to range from 4.6 to 30 Gy [92IAE]. Here, reproduction was also found to be a more radiation-sensitive endpoint, and dose rate plays an important role: an irradiation with gamma rays at a rate of 10 mGy/min showed no measurable effect on subsequent egg production up to doses as high as 8 Gy. Invertebrates were found to be, in general, much less (typically by a factor of 100) sensitive to radiation than vertebrates. This has been ascribed to the fact that they have very little cell division and differentiation. Again, their reproduction can be influenced by much lower doses of radiation.

In summary, reproduction has been found to be the most important and limiting endpoint in terms of survival of an animal population. Acute doses below 0.1 Gy are very unlikely to produce persistent, measurable changes in populations and communities of terrestrial animals [75Tur]. If the irradiation is chronic, dose rates of less than 1 mGy/d are not expected to lead to observable changes in terrestrial animal populations. In aquatic populations even dose rates of 10 mGy/d would not induce any observable modifications in populations [78Bla].

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