11 Exposures from natural and man-made radiation sources

Natural background form the baseline upon which all man-made exposures are added and against which these exposures may be compared. Main contributors to the natural radiation exposure of man are radiations of cosmic origin or radionuclides present in the earth's crust including the human body itself. Largely depending on altitudes above sea level, geomagnetic altitudes and geological external conditions worldwide and internal doses from natural radiological sources vary from 1 to 10 mSv annually with an average of 2.4 mSv a^{-1}. Nearly 50 % is from indoor inhalation of ^{222}Rn and its progeny.

11.1 Introduction

The exposure of man to ionizing radiation from natural sources is a continuing and inescapable feature of live on earth. For most induviduals, this natural background exposures are much more significant than the exposures caused by man-made sources. Exceptions that apply to certain individuals are some exposures caused by medical radiation procedures, through mishandling of radiation sources, in accidents allowing radionuclides to be released to the environment, and at some workplaces. In all cases, the natural background source form the baseline upon which all man-made exposures are added, and it is a common level against which these exposures may be compared.

Essentially there are two main contributors to the natural radiation exposure of man: charged and uncharged particles generated by high-engery particles of cosmic origin incident on the earth's atmosphere, and radioactive nuclides originating either by interaction of cosmic-ray particles in the earth's atmosphere or being naturally present in the earth's crust everywhere in the environment, including the human body itself. From these sources dose to man arise from both external and internal exposure.

Exposure from extra-terrestrial sources (cosmic radiations and cosmogenic radionuclides) and of terrestial origin (e.g. ^{40}K, and radionuclides of the uranium and thorium decay chains) contribute to the natural background at a comparatively constant level, although largely depending on geological conditions, altitudes above sea level, and geomagnetic latitudes.

Origin and kinds of galactic and solar cosmic radiations and reference doses to members of the world population arising from these external sources as well as internally from ingestion of cosmogenic radionuclides are dealt with in Section 11.2. Exposure pathways and doses from terrestrial sources of natural origin are described in Section 11.3 with special emphasis to the inhalation of radon progeny of the uranium and thorium decay chains. In Section 11.4 exposures are summarized due to modification of natural sources by human activities, e.g. release of natural radionuclides to the environment in mineral processing and fossil fuel combustion. Finally, i.e. in Section 11.5, the worldwide average exposures from the single sources of natural origin and the total dose by adding up the various components of the effective dose are given together with the normal ranges of these exposures. These numbers serve as the basis for evaluating the present (year 2000) doses from man-made sources of artificial origin and of occupational radiation exposures.

Quantitative information on sources and doses from natural and enhanced natural exposures due to industrial activities as well as from exposures to the public from man-made sources of radiation such as medical and occupational exposures, and those from peaceful and military defence uses of nuclear energy is based on data recently published by the United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR in its 2000 Report [00U].

11.2 Exposures by cosmic radiation and cosmogenic radionuclides

11.2.1 Origin and kinds of cosmic radiation

Galactic cosmic rays incident on the top of the atmosphere consist of a nucleonic component (98 %), and electrons (2 %). The nucleonic component is primarily protons (88 %) and α-particles (11 %), with the remainder heavier nuclei. These primary cosmic particles have an energy spectrum that extends from 10^8 eV to over 10^{20} eV.

Another component of cosmic rays is generated near the surface of the sun by magnetic disturbances. These solar particle events are comprised mostly of protons of energies generally below 10^8 eV and only rarely above 10^{10} eV. They can produce significant dose rates at high altitudes, but only the most energetic affect dose rates of background level. Solar particle events are highly variable in intensity and of short duration, typically a few hours. They have a negligible impact on long-term doses to the general population. The most significant long-term solar effect is the 11-year cycle in solar activity, which generates a corresponding cycle in total cosmic radiation intensity.

The magnetic field of the earth partly reduces the intensity of cosmic radiation reaching the top of atmosphere. The form of the earth's field is such that only particles of higher energies can penetrate at lower geomagnetic latitudes.

The high-energy particles incident on the atmosphere interact with atoms and molecules in the air and generate a complex set of secondary charged and uncharged particles, including protons, neutrons, pions and low-*Z* nuclei. The secondary nucleons in turn generate a cascade of more nucleons in the atmosphere. Because of their longer mean free path, neutrons dominate the nucleonic component at lower altitudes. The neutron energy distribution peaks between 50 and 500 MeV as well as around 1 MeV (produced by nuclear deexcitation) are important in dose assessment.

The pions generated in nuclear interactions are the main source of the other components of the cosmic radiation field of the atmosphere. The neutral pions decay into high-energy photons, which produce high-energy electrons, which in turn produce photons (photon/electron cascade). Electrons and positrons dominate the charged particle fluence rate at middle altitudes. The charged pions decay into muons, the dominant component of the charged-particle flux at ground level.

11.2.2 Exposures by cosmic radiations

At ground level, the muon component is the most important contributor to dose. At air craft altitudes, neutrons, electrons, positrons, and photons are the most significant components. At higher altitudes, the heavy nuclei components must by considered, too.

11.2.2.1 World population external exposures at ground level

At ground level, the dominant component of the cosmic-ray field is muons with energies mostly between 1 and 20 GeV. These contribute about 80 % of the absorbed dose rate in free air from the directly ionizing radiation. The remainder dose comes from electrons produced by the muons or present in the electromagnetic cascade. As altitude increases, the electrons become more important contributors to the dose rate.

According to the UNSCEAR 1988 Report [88U] the world population dose rate from directly ionizing radiation is 31 nGy h^{-1} at sea level. The dose rate is to be considered as averages over the 11-year solar cycle, weighted by the fraction of 54 % of world population living in the northern and southern hemisphere at latitudes below 30°. Since mostly muons are involved, a radiation weighting factor of unity is appropriate yielding the same values for the effective dose rate, i.e. 31 nSv h^{-1}.

The world average effective dose rate at sea level from neutrons of isotropic incidence obtained by applying a neutron fluence energy distribution equally to 720 nSv h^{-1} per neutron cm^{-2} s^{-1} is 5.5 nSv h^{-1}.

For both the ionizing and neutron components, there is a substantial altitude effect (see Fig. 11.1 [93U] and Fig. 11.2 [93U]). For the directly ionizing and photon component the population-weighted average dose rate is 1.25 times that at sea level, for neutrons 2.5 times. Consequently the world effective dose rate from exposures outdoors is 39 nSv h^{-1} for the directly ionizing and photon component, and 14 nSv h^{-1} for the neutron component.

Assuming a shielding effect of buildings of 20 % (shielding factor 0.8) and an indoor occupancy of 80 % of time for both cosmic radiation charged particles, photons and neutrons the world average effective dose rate from the directly ionizing and photon component of cosmic rays is about 25 nSv h^{-1} or 219 μSv a^{-1}, the corresponding average values for the neutron component are 9 nSv h^{-1} or 78 μSv a^{-1}. The total world average external annual effective dose is thus 297 μSv a^{-1}.

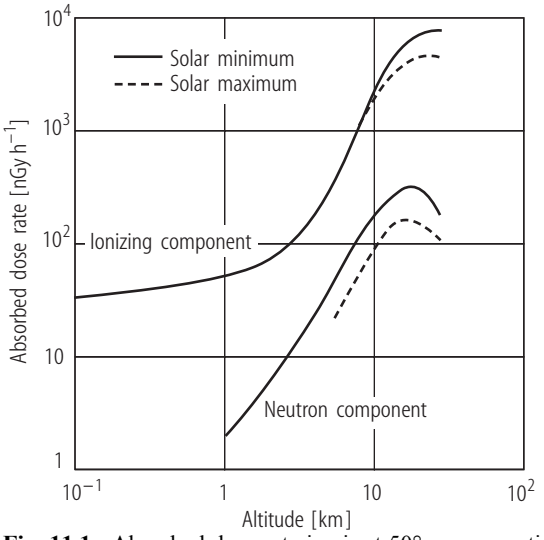

Fig. 11.1. Absorbed dose rate in air at 50° geomagnetic latitude from the ionizing and neutron components of cosmic rays as a function of altitude; [93U].

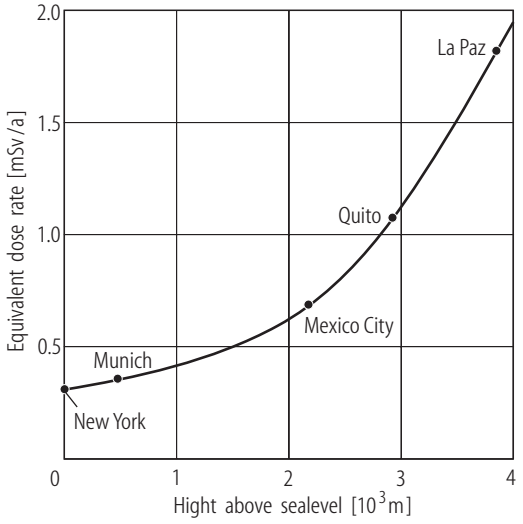

Fig. 11.2. Equivalent dose rate of selected populations at various hights above sea level; data taken from [93U].

11.2.2.2 Exposures by cosmic radiations at aircraft altitudes

Aircraft passengers and crew are subject to cosmic radiation exposure rates partly much higher than the rates at ground level, depending on the particular path taken through the atmosphere in terms of altitude above sea level (see Fig. 11.1) and geomagnetic latitude (see. Fig. 11.3 [00U]).

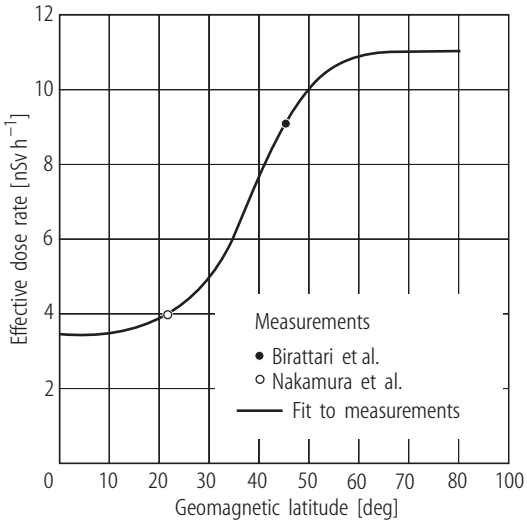

Fig. 11.3. Geomagnetic latitude variation in effective dose rate from cosmic ray neutrons at sea level; data taken from [00U].

For altitudes of 9 - 12 km (commercial subsonic aircraft) at temperate latitudes, the effective dose rates are in the range of 5 - 8 μSv h^{-1}, such that for a transatlantic flight of 6 hours from Europe to North America the route dose would be 30 - 50 μSv. At equatorial latitudes, the dose rates are lower and in the range of 2 - 4 μSv h^{-1}, such that for a 10 hours flight from Europe to South Africa the route dose would be 20 - 40 μSv.

For crew members the average annual flight duration, i.e. the time between leaving the terminal before take-off and returning after landing multiplied by the annual number of flights, is assumed to be 500 hours (300 - 900 h). For occasional flyers an average of 10 hours (3 - 50 h) and for frequent flyers (business flyers or couriers) of 100 hours (50 - 1 200 h) is assumed annually.

A small portion of passengers and flight crews travel at higher altitudes of about 18 km on supersonic transports. Effective dose rates of 10 - 20 μSv h^{-1} are normally found with possible significant dose contributions from solar particle events.

11.2.2.3 Internal exposures by cosmogenic radionuclides

The interactions of cosmic-ray particles in the atmosphere by high energy spallation interactions produce a number of radionuclides, including ^{3}H, ^{7}Be, ^{14}C and ^{22}Na at a global inventory of 1275, 413, 12750, and 0.44 PBq, respectively. Only for these elements, which are of metabolic importance in the human body, doses are worth mentioning. UNSCEAR [93U] previously assessed the annual effective doses from these cosmogenic radionuclides to be 12 μSv (^{14}C), 0.15 μSv (^{22}Na), 0.03 μSv (^{7}Be), and 0.01 μSv (^{3}H), respectively, or in total about 10 μSv.

11.3 Terrestrial radiation

Naturally occuring radionuclides of terrestrial origin – primordial radionuclides – are present in various degrees in all media of the environment, including the human body itself. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in significant quantities in these materials.

Irradiation of the human body from external sources is mainly by γ-radiation from radionuclides in the ^{238}U and ^{232}Th series and from ^{40}K. These radionuclides are also present in the human body from ingestion and inhalation, and irradiate the various organs with α- and β-particles, as well as γ-rays. Some other terrestrial radionuclides, including those of the ^{235}U series, ^{87}Rb, ^{138}La, ^{147}Sm, and ^{176}Lu, exist in nature but at such low levels that their contributions to the dose in humans are small.

11.3.1 External exposures

11.3.1.1 Outdoors

External exposure outdoors arise from terrestrial radionuclides present at trace levels in all soils depending on the types of rock from which the soils originate. Gamma-spectrometric measurements indicate that the three components of the external radiation field, i.e. from the γ-emitting radionuclides in the ^{238}U and ^{232}Th series and ^{40}K, make approximately equal contributions to the externally incident γ-radiation dose to individuals in typical situations both outdoors and indoors.

The activity concentration of ^{40}K in soils is an order of magnitude higher than that of ^{238}U or ^{232}Th series. UNSCEAR [00U] suggested median values for ^{40}K, ^{238}U, and ^{232}Th series of 400, 35, and 30 Bq kg^{-1}, and population-weighted values of 420, 33, and 45 Bq kg^{-1}. Based on corresponding dose coefficients of 0.0417, 0.462, and 0.604 nGy h^{-1} per Bq kg^{-1} the total median and population weighted absorbed dose rates in air were calculated to be 51 and 60 nGy h^{-1}, respectively. The lowest values of the absorbed dose rate in air outdoors are in Cyprus, Iceland, Egypt, the Netherlands, Brunei, and the United Kingdom, all less than 40 nGy h^{-1}, and the higher values are in Australia, Malaysia, and Portugal, all greater than 80 nGy h^{-1}.

In addition to variations from place to place, the ambient background γ-dose rate in air at any specific location is not constant in time. It is subject to considerable fluctuation, in particular from the removal of ^{222}Rn progeny in air by rainfall, soil moisture and snow cover.

There are small areas of markedly high absorbed dose rates in air throughout the world that are associated with thorium-bearing and uranium-bearing minerals in soil, such as monazite sand deposits of high levels of thorium as in Guarapari in Brazil (beaches, population size: 73 000; from 90 - 90 000 nGy h^{-1}), Yangiang in China (population size: 80 000; <370 nGy h^{-1} average), the states of Kerala and Madras in India (costal areas, population size: 100 000; 200 - 4 000 nGy h^{-1}), and Ramsar and Mahallat in Iran (population size: 2 000; 70 - 17 000 nGy h^{-1}), in the latter areas caused by ^{226}Ra deposited from waters flowing from hot springs [00U].

In summary the population weighted absorbed dose rate in air outdoors from terrestrial γ-radiation is 60 nGy h^{-1}.

11.3.1.2 Indoors

Indoor exposure to γ-rays is mainly determined by the materials of construction and their surrounding configuration indoors, and inherently greater than outdoor exposure if earth materials have been used. When the duration of occupancy is taken into account, indoor exposure becomes even more significant.

From surveys of absorbed dose rates in air inside dwellings the population-weighted average of the absorbed dose rate proved to be 84 nGy h^{-1} with national averages ranging from 20 - 200 nGy h^{-1} [00U]. The lowest values are in New Zealand, Iceland and the United States, all below 40 nGy h^{-1}, which probably reflects the preponderance of wood-frame houses. The higher values (95 - 115 nGy h^{-1}) are in Hungary, Malaysia, China, Albania, Portugal, Australia, Italy, Spain, Sweden, and Iran, which must reflect wide use of stone or masonry materials in buildings.

11.3.1.3 Effective dose from external exposures

To estimate the annual effective doses, account must be taken of the conversion coefficient from absorbed dose in air to effective dose, and the outdoor and indoor occupancy factors. The averages of the numerical values of these parameters vary with the age of the population and the climate at the location considered. In the UNSCEAR 1993 Report [93U], the Committee used 0.7 Sv Gy^{-1} for the conversion coefficient from absorbed dose in air to the effective dose received by adults, and 0.8 for the indoor occupancy factor, i.e. the fraction of time spent indoors and outdoors is 0.8 and 0.2, respectively.

From the data summarized in Sections 11.3.1.1 and 11.3.1.2 (outdoor population weighted absorbed dose rate in air: 60 nGy h^{-1}; indoors: 84 nGy h^{-1}) the worldwide average of the effective dose rate is 55 nGy h^{-1}, and of the annual effective dose 486 μSv (outdoors: 74 μSv; indoors: 412 μSv). The latter is for induvidual countries generally within the 300 - 600 μSv range. For children and infants the values are about 10 % and 30 % higher depending on the conversion coefficient from absorbed dose in air to effective dose.

11.3.2 Internal exposures

Internal exposures arise from the intake of terrestrial radionuclides by inhalation and ingestion. Doses by inhalation result from the presence in air of dust particles containing radionuclides of the ^{238}U and ^{232}Th decay chains.

The dominant component of inhalation exposure is the short-lived decay products of radon, which is considered separately in Section 11.3.2.2.

Doses by ingestion are mainly due to ^{40}K and to ^{238}U and ^{232}Th series radionuclides present in foods and drinking water.

The dose rate from ^{40}K can be determined directly from external measurements *in vivo* of its concentration in the human body. The dose rate from uranium- and thorium-series radionuclides in the body is estimated either from measured activity concentrations after chemical analyses of tissues or from results of analyses of radionuclide contents of foods and drinking water, along with bioassay data and the knowledge of the metabolic and biokinetic behaviour of the radionuclides.

11.3.2.1 Radionuclides other than radon

Intake by inhalation of natural radionuclides other than radon and its short-lived decay products makes only a minor contribution to internal exposure. They cover long-lived radon decay products due to disintegration of ^{222}Rn in air and radionuclides of the ^{238}U and ^{232}Th series present in air because of resuspended soil particles [00U]: ^{210}Pb (500 μBq m^{-3}), ^{210}Po (50 μBq m^{-3}), ^{238}U (1 μBq m^{-3}), ^{235}U (0.05 μBq m^{-3}), ^{232}Th and ^{230}Th (each 0.5 μBq m^{-3}), ^{228}Th (1 μBq m^{-3}), ^{228}Ra and ^{226}Ra (each 1 μBq m^{-3}). That means the highest concentration to be for ^{210}Pb, and those for the others to be lower by factors of 10, 500, 1 000, and 10 000.

Ingestion intake of natural radionuclides depends on the consumption rates of food and drinking water and on the radionuclide concentrations. Based on reference consumption profiles, reference water balance information and reference values for concentrations of uranium- and thorium-series radionuclides in foods and drinking water UNSCEAR [00U] derived the follwing reference values for annual intakes: ^{210}Po (58 Bq), ^{210}Pb (30 Bq), ^{228}Ra (15 Bq), ^{226}Ra (22 Bq), ^{238}U (5.7 Bq), ^{230}Th (3.0 Bq), ^{228}Th (3.0 Bq), ^{232}Th (1.7 Bq), ^{235}U (0.2 Bq).

The age-weighted (age distribution: infants 0.05, children 0.3, adults 0.65) committed annual effective dose from inhalation of uranium- and thorium-series radionuclides in air is 5.8 μSv, that from ingestion is roughly 25 times higher, i.e. 140 μSv. The annual committed effective dose from the reference values of uranium- and thorium-series radionuclides in tissues evaluated in the UNSCEAR Report of 1988 [88U] and adjusted to revised tissue weighting factors [93U] is 130 μSv in close agreement with the estimate of 110 μSv derived for adults from the dietary consumption by adults of reference concentrations of radionuclides in foods and water.

Potassium is more or less uniformly distributed in the human body following intake in foods, and its concentration in the body is under homeostatic control. The annual equivalent dose in tissues from ^{40}K and hence the annual effective dose is 165 and 185 μSv for adults and children, respectively, i.e. 170 μSv weighted for age.

The total committed annual effective dose from inhalation and ingestion of terrestrial radionuclides weighted for age is 316 μSv of which 170 μSv is from ^{40}K and 146 μSv is from the long-lived radionuclides in the uranium and thorium series.

11.3.2.2 Radon and decay products

11.3.2.2.1 Sources, health risks and exposure-to-dose conversion

Inhalation of radon and its short-lived decay products in the atmosphere are the most important contributors to human exposure from natural sources. ^{222}Rn and ^{220}Rn are the gaseous radioactive products of the decay of the radium isotopes ^{226}Ra and ^{224}Ra, which are present in all terrestrial materials. Some of the atoms of these radon isotopes are released from the solid matrix of the material by recoil when radium decays, and escape from the mineral grain into the pore space. Radon atoms entering the pore space are then transported by diffusion and advection through this space until they in turn decay or are released into the atmosphere outdoors or indoors, i.e. into buildings (see Fig. 11.4 and 11.5 [01B]).

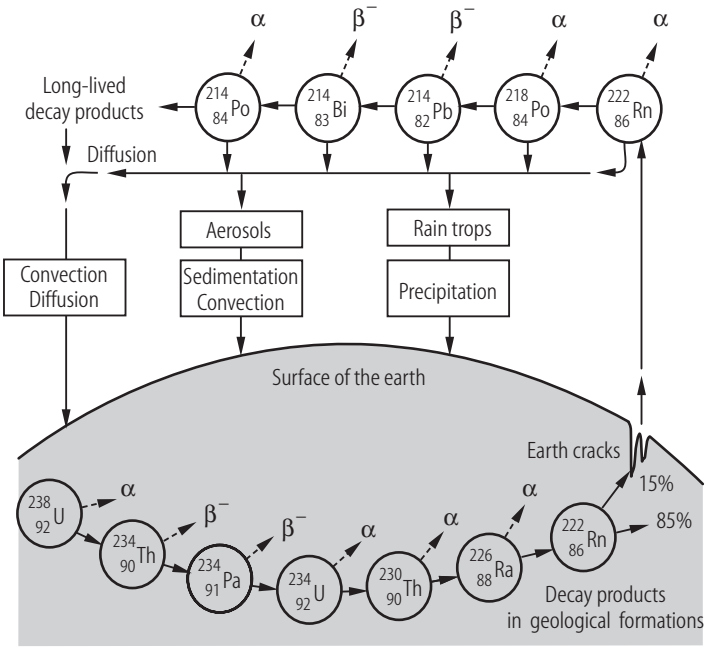

Fig. 11.4. Formation of ^{222}Rn by decay of ^{226}Ra in uranium-bearing minerals, release of radon atoms from mineral grain into pore space and partial transportation by diffusion into the atmosphere outdoors or indoors; redrawn from [01B].

Inhalation of the short-lived decay products of ^{222}Rn, and to a lesser extent of the decay products of ^{220}Rn (thoron), and their subsequent deposition along the walls of the various airways of the bronchial tree provide the main pathway for radiation exposure of the lungs, predominantly by α-particles. From miners studies it is known that the α-particle irradiation of the secretory and basal cells of the upper airways is responsible for the lung cancer risk. Thus, the damage to these critical target cells of the respiratory tract depends in a sensitive manner on the source/target geometry.

The dose that is relevant to the amount of lung-cancer risk depends critically on those environmental factors that affect the probability of the radon decay products to be deposited near the critical target cells after inhalation, i.e. the fraction of radon decay products which is attached to aerosols, the size distribution of the aerosols, and the unattached fraction of radon decay products, as well as the radon activity concentration, the equilibrium between radon and its decay products, the subject's inhalation rate, and the time of exposure.

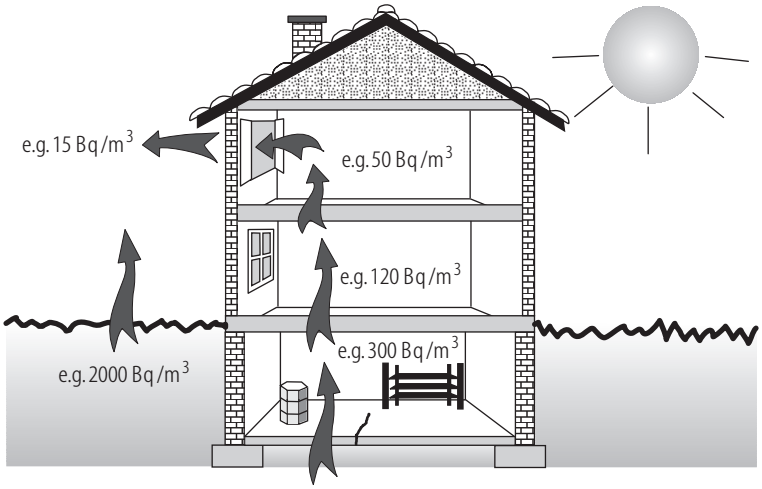

Fig. 11.5. Indoor diffusion of ^{222}Rn and its distribution in a building; redrawn from [01B].

Absorbed doses to the critical cells and effective doses are determined by applying exposure-to-dose conversion factors. For ^{222}Rn the range of these values derived from epidemiological studies and physical dosimetry varies from 6 to 15 nSv (Bq h m^{-3})$^{-1}$. As in its 1993 Report [93U] UNSCEAR applies in its 2000 Report [00U] the dose conversion factor of 9 nSv (Bq h m^{-3})$^{-1}$. Since there are no epidemiological data for lung cancer risk following ^{220}Rn exposure from which to derive a conversion convention for thoron decay products the value of 40 nSv (Bq h m^{-3})$^{-1}$ derived from the ICRP Human Respiratory Tract Model [94I] (see Chapter 7) was used for the estimation of equilibrium equivalent thoron doses for indoor and outdoor exposures.

11.3.2.2.2 Air concentrations outdoors and indoors

Recent results of radon measurements outdoors tend to confirm the estimates of typical outdoor ^{222}Rn and ^{220}Rn concentrations made in the UNSCEAR 1993 Report [93U] of 10 Bq m^{-3} for each radon isotope (range: for ^{222}Rn 1 to >100 Bq m^{-3}; for ^{220}Rn much smaller due to the short half-live).

The equilibrium factor, defined as the ratio of the actual potential α-energy concentration to that, if all the decay products in each series were in equilibrium with the parent radon, is suggested for radon in the outdoor environment to be 0.6 for ^{222}Rn, and 0.01 for ^{220}Rn, respectively [00U].

For radon indoor concentrations the corresponding representative data are [00U]:
^{222}Rn activity concentration 40 Bq m^{-3}, equilibrium factor 0.4;
^{220}Rn activity concentration, 10 Bq m^{-3}, equilibrium factor 0.03.

11.3.2.2.3 Effective doses

For the above worldwide arithmetic outdoor and indoor radon gas concentrations, representative equilibrium factors for the actual potential α-energy concentration for outdoor and indoor occupancy factors of 0.2 and 0.8 corresponding to annually 1760 and 7000 h, and the dose conversion factors of 9 and 40 nSv (Bq h m^{-3})$^{-1}$ for ^{222}Rn and ^{220}Rn, respectively, the following annual effective doses are derived [00U]:

^{222}Rn

Outdoors: 10 Bq m^{-3} × 0.6 × 1 760 h × 9 nSv (Bq h m^{-3})$^{-1}$ = 95 μSv
Indoors: 40 Bq m^{-3} × 0.4 × 7 000 h × 9 nSv (Bq h m^{-3})$^{-1}$ = 1 000 μSv

^{220}Rn

Outdoors: 10 Bq $m^{-3} \times 0.01 \times 1\,760$ h $\times$ 40 nSv (Bq h $m^{-3})^{-1}$ = 7 μSv
Indoors: 10 Bq $m^{-3} \times 0.03 \times 7\,000$ h $\times$ 40 nSv (Bq h $m^{-3})^{-1}$ = 84 μSv

For completeness, the contribution to the annual effective dose from dissolution of the radon gases in blood with distribution throughout the body is [00U]:

^{222}Rn

Outdoors: 3 μSv
Indoors: 48 μSv

^{220}Rn

Outdoors: 2 μSv
Indoors: 8 μSv

The total global annual average of the effective dose from inhalation of ^{222}Rn and its decay products present in air, from dissolution of radon gas in blood and ingestion of radon gas with tap water (2 μSv) [93U] is 1148 μSv with fractions of about 95 % from inhalation outdoors and indoors and 5 % from dissolved radon gas in blood and from ingestion of tap water. The annual effective dose from ^{220}Rn is 101 μSv with fractions of about 90 % from inhalation and 10 % from thoron dissolution in blood.

These estimates of the global averages of the annual effective doses for radon only define the normal radon and thoron exposures. One may expect to find many large populations around the world in the order of 10^6 individuals, whose average exposures differ from the above global averages by a factor of more than 2, and up to a factor of more than 10 for many smaller populations in the order of 10^4 individuals.

11.4 Enhanced exposures form industrial activities

There are numerous circumstances in which materials containing natural radionuclides are recovered, processed and used, causing extra or enhanced population exposures. These exposures are those arising from the mineral processing industries and from fossil fuel combustion by emission of radionuclides by fly ash to air and water, and subsequent eventual intake by humans. Landfills after dredging or wastes disposed on land may also provide pathways of exposure.

Main industries are:

- Phosphate processing
- Metal ore processing
- Uranium mining
- Fossil fuels for electric power production
- Oil and gas extraction.

Estimated maximum exposures are greatest for phosphoric acid production and for the mineral-sands-processing industries. Although effective dose rates of the order of 100 μSv a^{-1} could be received by a few local residents, levels of the annual per caput effective doses of 1 - 10 μSv would be more common [00U]. These exposure rates constitute a negligible component of the total annual effective doses from all natural sources of radiation.

11.5 Worldwide average exposure from natural and man-made sources

Worldwide average annual exposure by adding the various components described in Sections 11.2 to 11.4 proves to be about 2400 μSv effective dose. The sources of exposure and the single values of the worldwide annual effective doses are summarized in Table 11.1 in μSv and in % of the total effective dose, respectively. It should be stated that this average annual effective dose does not pertain to any one individual, since there are wide distributions of exposures from each source, and the exposures combine in various ways at each location, depending on the specific concentrations of radionuclides in the environment and in the human body, the latitude and altitude of the location and many other factors such as living habits.

Table 11.1. Average worldwide exposure to natural radiation sources

Source of exposure	Worldwide average of the annual effective dose		
	[μSv a^{-1}]	[% of total]	Typical range [μSv a^{-1}]
Cosmic radiation			
Directly ionizing and photon component	219	9.1	
Neutron component	78	3.2	
Cosmogenic radionuclides	10	0.4	
Total exposure from cosmic and cosmogenic sources	**307**	**12.7**	**300 - 2000**
External terrestrial radiation			
Outdoors	74	3.1	
Indoors	412	17.1	
Total external terrestrial exposure	**486**	**20.2**	**300 - 600**
Internal exposure: Inhalation			
Uranium and thorium series	6	0.2	
^{222}Rn + daughters	1148	47.5	
^{220}Rn + daughters	101	4.2	
Total inhalation exposure	**1255**	**51.9**	**200 - 10000**
Internal exposure : Ingestion			
^{40}K	170	7.1	
Uranium and thorium series	140	5.8	
Total ingestion exposure	**310**	**12.9**	**200 - 800**
Internal exposure: from blood			
^{222}Rn, ^{220}Rn + daughters	**45**	**1.9**	**10 - 400 (?)**
Enhanced exposures:			
from industrial activities	**<10**	<0.4	**1 - 10**
Total (rounded)	**2400**	**100.0**	**1000 - 10000**

The normal ranges of exposure to the various components of natural radiation are also indicated in Table 11.1. This accounts for common variations in exposures, but excludes those individuals at extreme ends of the distributions. On this basis, the worldwide average annual exposure to natural radiation sources of 2400 μSv being the present estimate of the central value would generally be expected to be in the range of 1000 - 10000 μSv. About 15 % of the worldwide average exposure is due to cosmic and cosmogenic sources, about 20 % to external terrestrial exposure, in the order of 10 % is from ingestion of natural radionuclides and about half of the total annual effective dose is due to the inhalation of both radon isotopes ^{222}Rn and ^{220}Rn together with their radioactive decay products.

The present (year 2000) worldwide total annual per caput effective dose from man-made sources is about 410 μSv (400 μSv from diagnostic medical examinations, 5 μSv from atmospheric nuclear weapons testing, 0.2 μSv from nuclear power production, and 2 μSv from the Tschernobyl nuclear reactor accident [00U]), i.e. only about 15 % of the dose from natural sources. The largest contribution to exposures of individuals worldwide is from medical diagnostic procedures (about 98 %), only 0.05 % from nuclear power production.

There are a number of occupations, in which workers are exposed to enhanced natural and man-made sources of radiation, i.e. to doses that are directly due to the work. Enhanced natural sources are air travel (crew), mining (other than coal), coal mining, mineral processing, and radon at above ground work places. Man-made sources are the nuclear fuel cycle (including uranium mining), industrial uses of radiation, military defence activities, medical uses of radiation, education, and veterinary. The present (year 2000) average annual effective dose from occupational exposure to enhanced natural sources is 1800 μSv, due to man-made sources is 600 μSv [00U], i.e. about 75 % and 25 % , respectively, of the worldwide average annual per caput effective dose from natural background of 2400 μSv.

11.6 References

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