11 Environmental Radioactivity

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."

Richard Feynman

Natural radioactivity from the environment has three components:

- cosmic rays,
- terrestrial radiation,
- ingestion (eating, drinking, and breathing).

Cosmic rays from our Sun and our galaxy and terrestrial radiation from the Earth crust as well as incorporations of radioisotopes from the biosphere represent whole-body exposures. A special role is played by the inhalation of the radioactive noble gas radon which, in particular, represents an exposure for the lungs and the bronchi. In addition to these natural sources further exposures due to technical, scientific, and medical installations developed by modern society occur. The existence of natural radioactive substances, however, demonstrates that radioactivity and the development of life coexisted since the very earliest times on our planet.

coexistence of life and radioactivity

11.1 Cosmic Rays

Our Milky Way is the dominant source of high-energy cosmic rays. The low-energy particles predominantly originate from our Sun. Primary cosmic rays consist largely of protons ($\approx$ 85%) and helium nuclei ($\approx$ 12%). Only 3% of primary nuclei are heavier than helium. Nevertheless all elements of the periodic table occur as particles in primary cosmic rays (see also Fig. 9.6). Apart from these baryonic, strongly interacting components of cosmic rays, there are also electromagnetically interacting electrons and photons in primary cosmic rays as well as weakly interacting neutrinos. Even though the flux of neutrinos – particularly from the Sun – is extremely high, neutrinos play only a minor role in the field of radiation protection due to their low interaction probability.

cosmic rays

Primary cosmic rays interact with atoms or, more precisely, with atomic nuclei of the atmospheric gas and produce a large variety of elementary particles. Because of the high energies of primary

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_11,

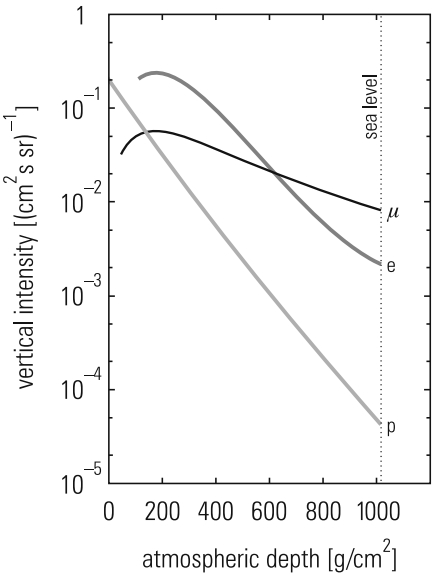


Figure 11.1
Altitude dependence of proton, electron, and muon fluxes in the atmosphere

muon component

proton component
electron component

cosmic rays, cascades of secondary and tertiary particles will develop in the atmosphere. The dominant component reaching the surface of the Earth consists of so-called muons. Muons are particles which have similar properties to electrons with the difference that they are about 200 times heavier and are unstable. The flux of these muons at sea level amounts to about one particle per cm^2 and minute through a horizontal area, see also Sect. 9.4. Figure 11.1 shows the proton, electron, and muon components as function of the atmospheric depth.

The secondary electron flux is relatively strongly attenuated in the atmosphere. However, muons are very penetrating particles, which can even be measured at great depths underground.

The exposure due to cosmic rays of a person in Western Europe and in the United States amounts to about 0.3 mSv/yr. It varies with geomagnetic latitude because the Earth's magnetic field shields charged primary cosmic rays to a certain extent. At the North Pole the radiation exposure is somewhat higher ($\approx$ 0.4 mSv/yr) while it is less at the equator ($\approx$ 0.2 mSv/yr). This is related to the different geomagnetic cutoff[1]. The exposure also varies strongly with

[1] Due to the magnetic dipole field of the Earth the cutoff momentum for primary cosmic radiation varies as $\cos^4 \lambda$, where λ is the geomagnetic latitude; the cutoff momentum is about 15 GeV/c at the equator (λ = 0 deg) and zero at the magnetic poles (λ = 90 deg). The atmospheric cutoff momentum due to the absorption of secondary cosmic rays in air amounts to about 2 GeV/c.

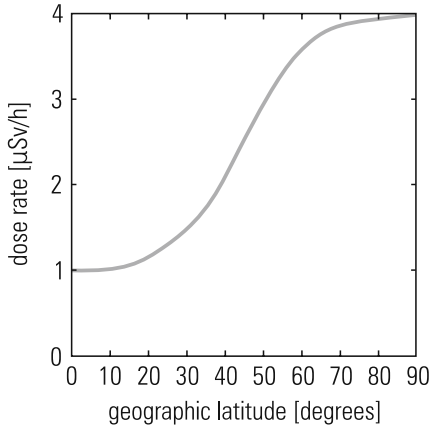


Figure 11.2
Average dose rate for flights at 10 km altitude as a function of the geographic latitude

altitude in the atmosphere since with increasing height the shielding effect of the air is reduced. For example, the exposure on Mt. Everest is 20 mSv/yr while it is about 1.2 mSv/yr in the Alps. At the altitudes of normal passenger flights (10–14 km), the dose rate is about 3 to 5 µSv per hour. For passengers in high-altitude research aircraft ($\approx$ 20 km altitude) the dose rate is about 20 µSv per hour, although this does depend on the geomagnetic latitude. Figure 11.2 shows the dependence of the radiation exposure on the geographic latitude at flight altitudes of around 10 km.

The radiation exposure of astronauts has been measured with dosimetry telescopes on board the Russian Space Station MIR and the International Space Station (ISS). The exposures vary typically between 300 and 500 µSv per day inside the station and are around 500 µSv for an eight-hour space-walk of an astronaut. About 70% of this dose originates from the galactic cosmic-ray component and 30% from protons trapped in the radiation belt.[2]

Paleomagnetic investigations on rocks have shown that reversals of the magnetic polarity of the Earth have occurred at irregular intervals, ranging from tens of thousands to many millions of years, with an average interval of approximately 250 000 years. In these periods of magnetic field reversal, in particular, when the field is zero, our planet was exposed to an increased radiation by cosmic rays by a factor of about 3 to 5. Even so, no particular negative effects on the development of life on our planet have been observed at these times.

The dependence of the radiation exposure as a function of height in the atmosphere for average geographic latitudes is shown in Fig. 11.3.

[2] I am grateful to S. Burmeister, University of Kiel, for providing this information.

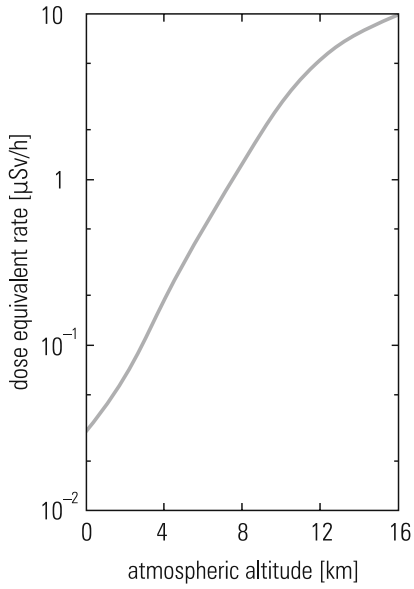
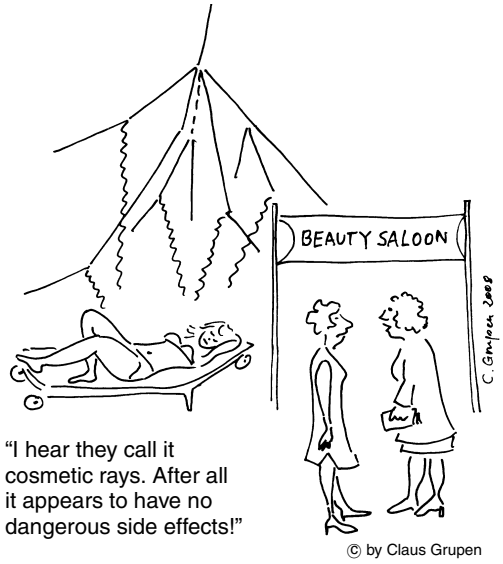


Figure 11.3
Variation of the dose rate with altitude in the atmosphere for average geographic latitudes (≈ 50 degrees)



11.2 Terrestrial Radiation

The soil of the planet Earth contains substances which are naturally radioactive and provide natural radiation exposures. The most important radioactive elements which occur in the soil and in rocks are the long-lived primordial isotopes potassium (^{40}K), radium (^{226}Ra),

natural radioactivity

and thorium (^{232}Th). The radioisotopes ^{40}K, ^{226}Ra, and ^{232}Th also occur in many building materials (such as concrete and bricks). Naturally, the radiation exposure varies with the environment depending on the concentration of radioisotopes in the ground. An average exposure for Europe and the United States is about 0.5 mSv/yr. However, this dose may exhibit strong regional variations. For example, for the area around the Black Forest in Germany dose rates up to 18 mSv/yr have been recorded. The highest exposures on Earth occur in Kerala on the western coast of India with 26 mSv/yr, in Brazil on the Atlantic coast with up to 120 mSv/yr, and in Ramsar in Iran with the record value of 450 mSv/yr. These exposures can be predominantly traced back to high thorium concentrations (up to 10%) in the ground.[3]

radon and evolution

Our natural environment therefore contains a large number of radioactive substances. Large populations have lived already over many generations in regions where the exposure is a factor of 10 higher compared to the average value without any visible disadvantages. The natural radioactivity from the environment was also substantially higher in early geological times (by a factor of 3 to 5 compared to today). It is assumed that such relatively high radiation doses were necessary to initiate the development of life on our planet. In the same way it might be suggested that the radiation from the natural environment was essential to speed up evolution and to create the biodiversity we observe today.

natural plutonium

It is interesting to note that plutonium also occurs as a natural isotope in the Earth's crust. ^{239}Pu with a half-life of 24 300 years is prominently produced by cosmic rays via the reaction

$$n + {}^{238}\mathrm{U} \longrightarrow {}^{239}\mathrm{U} + \gamma \qquad (11.1)$$

with two subsequent β^- decays via ^{239}Np:

$$^{239}\mathrm{U} \xrightarrow{\beta^-} {}^{239}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}\mathrm{Pu}\ . \qquad (11.2)$$

11.3 Incorporation of Radioisotopes

natural radioisotopes in air, in drinking water, and in food

The most important natural isotopes which occur in air, in drinking water, and in food, are the isotopes of hydrogen (tritium: ^{3}H), carbon (^{14}C), potassium (^{40}K), polonium (^{210}Po), radon (^{222}Rn), radium

[3] The mineral apatite occurring in the Brazilian state Minas Gerais contains large quantities of uranium and thorium in some places so that plants grown in these regions, which take up these radioactive isotopes from the soil, will produce an autoradiographic image if placed on a film.

(^{226}Ra), and uranium (^{238}U). These natural radioactive elements accumulate in the human body after being taken in with food, water, and air so that humans themselves become radioactive. The natural radioactivity of the human body is about 9000 Bq and originates predominantly from ^{40}K and ^{14}C. From this incorporation one can work out the average per capita exposure by incorporated natural radioactive substances to be about 0.4 mSv/yr. In addition to this, there is an exposure of the lungs due to the inhalation of the radioactive gas radon present in air. Figure 11.5 shows the production of ^{222}Rn in the uranium–radium chain and the release of this gas through cracks in rocks or ground into air.

natural radioactivity of humans

radiation exposure of the lungs

Figure 11.4
Low-level monitor system with dust sampler for the measurement of low beta activities, e.g. in radon-filter measurements (model LLM 500, mab Strahlenmesstechnik)

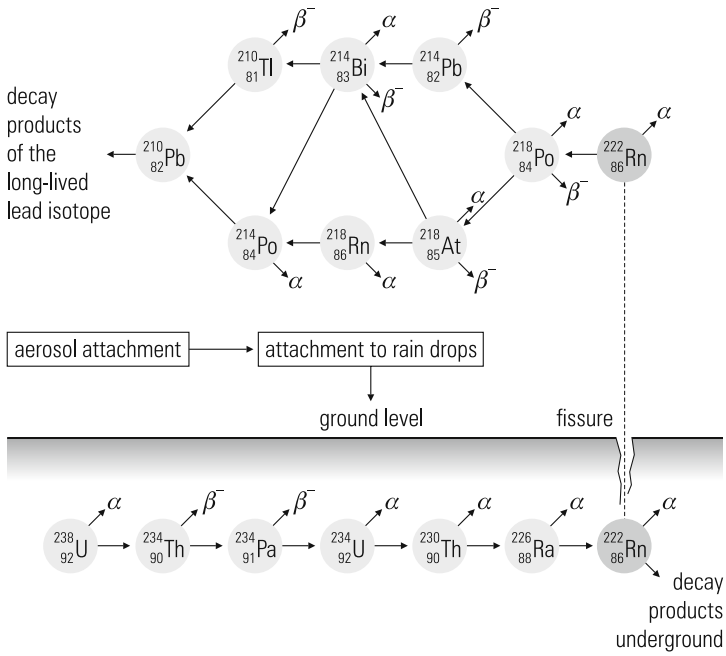


Figure 11.5
Production and release of ^{222}Rn

"10 000 nuclei decay per second in our bodies, and we worry about the price of petrol!"

radon inhalation

If the lung dose created by radon inhalation is converted into an equivalent whole-body dose, the result is an exposure of 1.1 mSv/yr, from the inhalation of this particular radon isotope alone.[4] However, it has not been demonstrated that low radon concentrations ($< 200\,\mathrm{Bq/m^3}$) might induce cancer. The total per capita exposure due to incorporations of natural radioactive substances from the environment amounts to approximately 1.5 mSv/yr.

In the same way as terrestrial radiation varies, also the radiation exposure by incorporation of radioisotopes from the biosphere is subject to substantial local variations. In badly ventilated houses the radon exposure alone can be a factor of 5 higher than the average. In poorly ventilated mines the radon exposure can even be higher than the average by factor of 100.[5]

radon exposure

In Table 11.1 the average per capita radiation exposures from natural sources are compiled. The average natural total radiation exposure amounts to about 2.3 mSv per year.

Figure 11.6 shows the fractions of radiation exposures by the different components from the environment in a graphical form.

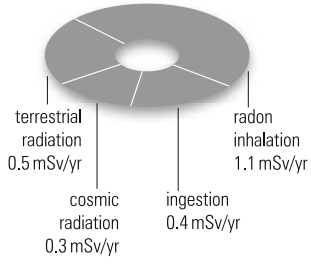


Figure 11.6
Breakdown of the exposures from the natural environment (2.3 mSv/yr)

[4] Snow samples e.g. from Mont Blanc exhibit a radioactivity which is 80 times higher compared to the snow on other mountains in the Alps. In contrast to other mountains in the Alps the granite rocks on Mt. Blanc have so many cracks that the noble gas radon can easily escape from the rocks. However, the radon concentration in the snow on Mt. Blanc is still quite harmless.

[5] In old Egyptian tombs and in pyramids radon concentrations of 6000 $\mathrm{Bq/m^3}$ have been found.

Table 11.1
Radioactive exposures of humans from natural sources

source	average exposure per year	highest values
cosmic radiation	≈ 0.3 mSv	10 mSv (at high altitudes)
terrestrial radiation	≈ 0.5 mSv	450 mSv (Ramsar, Iran)
incorporation of radioisotopes	≈ 1.5 mSv	5 mSv (extreme diet[6])

Humans cannot perceive ionizing radiation directly; and fortunately low-level radiation is mostly harmless. Nature possibly never saw the needs to equip humans with dedicated sensual organs for ionizing radiation, because such radiation does not present a hazard, and therefore does not require a warning.

11.4 Radiation Exposure by Technical Installations

The main usages of radioactive substances today are in scientific and technical installations. The dominant source for the per capita exposures, however, is the application of X, β, and γ rays in medicine in diagnostics and therapy. Some examples are given for illustration. Taking an X-ray image of the lungs gives a whole-body dose of about 0.1 mSv. An angiography of the arteries or an X-ray of a kidney represent an exposure of 10 mSv. In contrast, an X-ray image of the teeth leads to a dose of only 0.01 mSv.

X-ray diagnosis and therapy

therapy in nuclear medicine

The exposures by examination in nuclear medicine can, however, be quite substantial. The imaging of the thyroid gland with the iodine isotope ^{131}I leads to an equivalent whole-body dose of 33 mSv. In the past the liver was imaged with the gold isotope ^{198}Au corresponding to an equivalent whole-body dose of 3.6 mSv. These isotopes have now been mainly replaced by the short-lived ^{99m}Tc (a metastable state of ^{99}Tc). For example, myocardial perfusion scintigraphy nowadays frequently employs ^{99m}Tc. For a stress or resting examination of the heart an activity of 1 GBq is used which leads to an exposure of the patient of 7.6 mSv. Examinations using positron-emission tomography usually employ fluorine-18 de-

myocardial perfusion scintigraphy

positron-emission tomography

[6] This would include above-average concentration of radioisotopes in foodstuff, e.g. plants grown on soil with high levels of natural radioisotopes. In this context, even not counting as natural exposure, the high-level concentration of radioisotopes in mushrooms, venison, or reindeer steak after the Chernobyl accident has to be considered.

oxyglucose (^{18}F, half-life 110 minutes). For oncological investigations 400 MBq are usually injected corresponding to an exposure for patients of 7.6 mSv. ^{18}F is produced from ^{18}O by proton bombardment according to

$$p + {}^{18}\mathrm{O} \longrightarrow {}^{18}\mathrm{F} + n \ , \tag{11.3}$$

where the oxygen isotope is available in the form of $H_2{}^{18}O$. Since the half-life of the fluorine isotope is relatively long, it can be distributed locally after production at an accelerator. Short-lived positron emitters, such as ^{11}C ($T_{1/2} = 20$ min), ^{13}N ($T_{1/2} = 10$ min), ^{15}O ($T_{1/2} = 2$ min), ^{82}Rb ($T_{1/2} = 1.25$ min) can only be produced directly in hospitals which have a cyclotron in house.[7]

production of radioisotopes

In modern clinical practical work short-lived radioisotopes are predominantly used for diagnosis (e.g. ^{99m}Tc) to reduce the radiation exposure for the patient. Such radioisotopes can be produced e.g. by neutron bombardment. For example, ^{99m}Tc is obtained from neutron-activated molybdenum (see Chap. 9 on radiation sources). In the past short-lived isotopes were also created in the hospital with the help of so-called 'radioisotope cows'. For example, the short-lived γ-ray emitter ^{137m}Ba can be produced in the laboratory by milking the long-lived 'cow' ^{137}Cs (see Fig. 3.3, p. 22). Such a generator system is still used for calibration purposes in laboratories, but it is no longer used in nuclear medicine.[7]

radioisotope cow

surgery by robots

In many fields of diagnostics and surgery the experienced hand of the surgeon is replaced by the tremor-free movements of a robot. Miniature tools at the end of long catheters inserted into the femoral vein in the patient's thigh are frequently used for heart surgery. The tools can be controlled by robots, and this technique leads to better results in many cases. Such robots also spare the physicians many tiring hours of standing at an operation table wearing lead vests to limit the exposure to X rays or γ rays.

tumor therapy

It is obvious that the highest radiation exposures occur in the treatment of cancer. Here there is a compromise to be drawn between the expected therapeutical success and the radiation risk. In tumor therapy, maximum doses for single parts of the human body (i.e. not for the whole body) are extremely high: up to 100 Sv (!). A whole-body dose over a short period with such a dose would certainly lead to death from radiation sickness, since the lethal dose for the whole body amounts to about 4 Sv. A lethal dose is defined such that 50% of the exposed humans will die within 30 days without medical treatment. Cancer patients are able to survive a dose

[7] I am grateful to Dr. med. Oliver Lindner, physician at the heart and diabetes center of the university hospital of the Ruhr University Bochum, Germany, for this information.

of 100 Sv only because this dose is applied highly locally and, in general, only one organ is concerned. Furthermore, this high dose is applied in small sub-doses of several sievert with intervals thereby distributing the exposure over a number of days.

fractionated irradiation

per capita exposure

The average per capita exposure in Europe is currently somewhere around 1.9 mSv/yr from X-ray diagnosis and about 0.05 mSv/yr from other methods in nuclear medicine. This last average value is somewhat problematic since it relates to some very strong exposures received only by very few people. Other exposures from technical installations are almost negligible compared to the exposures due to medical diagnosis and treatment. In the 1960s, however, relatively large radiation exposures were observed from radioactive fallout after nuclear-weapons tests in the atmosphere, but these exposures have now faded away.

radioactive fallout

A large variety of nuclear isotopes is used in technical installations. For example, the isotopes tritium (^{3}H) and promethium (^{147}Pm) are used in phosphor screens, the α-ray emitter americium (^{241}Am) occurs in fire alarms of older types and plutonium (^{238}Pu), actinium (^{227}Ac), strontium (^{90}Sr), or cobalt (^{60}Co) are used in radioisotope batteries. In these batteries (see Chap. 9 on radiation sources) it is mainly the heat produced due to the absorption of radiation that is converted into electrical energy with the help of thermocouplers. Because of the long half-lives of certain radioisotopes ($T_{1/2}(^{238}\mathrm{Pu}) = 88\,\mathrm{yrs}$, $T_{1/2}(^{227}\mathrm{Ac}) = 22\,\mathrm{yrs}$, $T_{1/2}(^{90}\mathrm{Sr}) = 28\,\mathrm{yrs}$) these radioisotope batteries represent maintenance-free long-lived energy sources. Therefore, they are ideally suited for long-term space missions.

phosphor screens

fire alarms containing radioactive substances

radioisotope batteries

Radioactive substances are also used as anti-static materials and filling-level indicators. Phosphate fertilizers contain not only ^{40}K, but also other natural radioactive substances like uranium and thorium including their decay products. Up to the 1950s uranium compounds were also used for the production of pigments (with the colors yellow, red, brown, and black), in particular, for the glass and ceramic industry. The production of such 'radiating colors' is no longer allowed.

anti-static materials

filling-level indicators

phosphate fertilizers

The exposure from smoothly running nuclear power plants is very low ($< 0.01\,\mathrm{mSv/yr}$).[8] In this context it has to be mentioned that coal plants – in addition to the CO_2 emission, which presents a

nuclear power plants

[8] It has, however, to be mentioned that in the vicinity of recycling plants elevated radiation levels have been measured. For example, close to the recycling plant in La Hague, France, ground contaminations of 100 Bq/m^2 of ^{137}Cs and 10 Bq/m^2 of ^{60}Co have been found. In the exhaust air of this plant ^{85}Kr activity concentrations of several 1000 Bq/m^3 have been observed.

Filling-level measurement

A test tube partially filled with lead shot is irradiated by γ rays from the radioisotope ^{226}Ra. It is important to keep the γ-ray source and the scintillation counter (see figure) at the same level. The system of source and detector is now moved parallel to the axis of the test tube and the count rate is monitored in the detector as a function of height. When the source/detector system is lowered and reaches the level of the lead shot, the count rate will decrease drastically and will stay at a constant low level for larger depths. The count-rate dependence on the height allows to read accurately the filling level of the lead shot in the test tube.

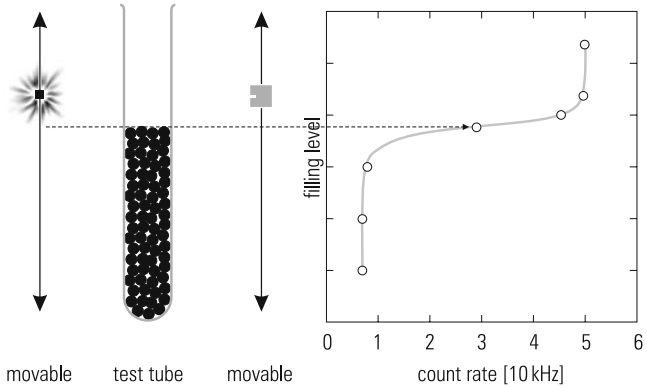


Figure 11.8
Filling-level measurement using a ^{226}Ra source

hazard for the Earth's climate – release more radioactive substances into the environment than nuclear power plants in normal operation conditions. The normal level of low-level radiation which is released by coal plants would provoke an outcry in the population if comparable quantities of radioactive substances were emitted by nuclear power plants. For example, in the United States about 800 tons of uranium are annually released into the air by coal plants. The use of effective filters, however, can reduce the emission of radioactive substances from coal plants quite substantially.

In Europe, a typical exposure of $\leq$ 0.01 mSv/yr is produced due to the use of radioactive substances and installations generating ionizing radiation in science and research.

An exception, of course, is the radiation exposure in 1986 after the reactor accident in Chernobyl in the former Soviet Union. In the year after the reactor catastrophe the average exposure in Western Europe may have been approximately 0.5 mSv. This exposure was mainly caused by the release of the radioactive isotopes ^{131}I, ^{137}Cs, ^{134}Cs, and ^{90}Sr, which entered into the food chain. The 50-years commitment dose of the reactor accident in Chernobyl can be esti-

Figure 11.7
Xenon/krypton ionization chambers for measuring the thickness and density of materials using radiation sources (VacuTec Meßtechnik GmbH)

Chernobyl accident

Gamma backscatter measurements

Filling-level measurements, i.e. absorption measurements, give information about the filling level and the absorber material. This type of measurement can only be done in the laboratory under well-controlled conditions. For applications in geology, e.g. in the investigation of boreholes, one is frequently interested in the chemical composition of the walls of the borehole to search for certain materials like oil, minerals, or heavy metals. The gamma backscatter method, as sketched in Fig. 11.9, is well-suited to this purpose. A γ-ray source (e.g. ^{226}Ra) emits γ rays of energy 186 keV isotropically. A detector records γ rays backscattered from the surrounding material. The detector itself is shielded from direct radiation from the source by a lead plate. The effectiveness of backscattering depends on the density and atomic number of the surrounding material. In Fig. 11.9, as well as a diagram of the apparatus, the count rate as a function of height in the borehole is plotted. The profile of the backscatter rate from layers of lead, water, and air clearly shows element-specific differences. The intensity of the backscatter rate permits to infer information on the density and the chemical composition of the surrounding layers. Measurements in a laboratory on air, water, aluminum, iron, and lead exhibit a clear correlation between the backscatter intensity R and the product of density ρ and the atomic number Z. Over a wide range, the backscatter rates can be approximated well by the empirical function $R \sim (\rho\, Z)^{0.2}$ (see Fig. 11.10).

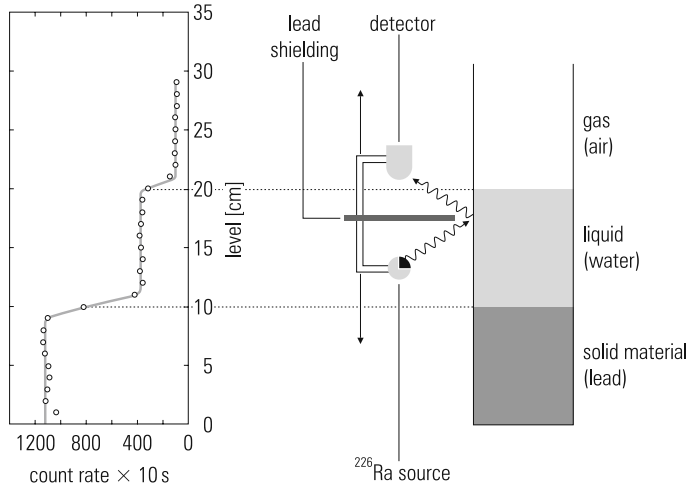


Figure 11.9
Dependence of the gamma backscatter rate on the product of density ρ and atomic number Z of the material

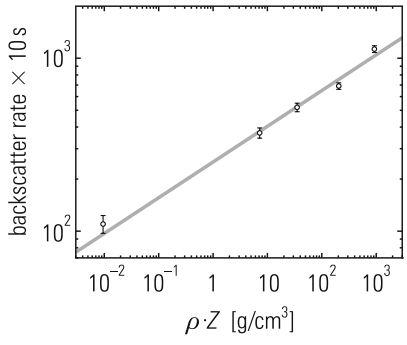


Figure 11.10
Backscatter rate in its material dependence for the gamma backscatter method

Measurement of the radioactivity of cigarette ash

The radioactivity of cigarette ash can be measured with a sensitive scintillation counter shielded against environmental radiation. The scintillation counter is fitted tightly into a thick-walled lead container, where it is exposed to radiation from cigarette ash (see figure). The measured radioactivity of the cigarette ash can be attributed to the following processes:

- Like all soil, the soil in which the tobacco plants are grown is radioactive. Normal soil contains the radioisotopes ^{226}Ra, ^{232}Th, and ^{40}K with total concentration of approximately 500 Bq/kg. Tobacco plants are frequently fertilized with phosphates which are rich in ^{238}U and ^{226}Ra. These radioisotopes from the soil and the phosphate fertilizer enter the tobacco plants via its roots. In the radium decay chain, the radioactive noble gas ^{222}Rn occurs as well as the relatively long-lived radioisotopes ^{210}Pb and ^{210}Po. These radioactive isotopes are partially (via the gaseous intermediate product ^{222}Rn) transferred into the air and may deposit themselves on the tobacco leaves. The content of radioisotopes in tobacco – depending on where it is grown and how it is fertilized – is subject to large fluctuations.
- In the process of smoking, a large number of aerosols is produced to which the decay products of the natural ^{222}Rn isotope can easily attach (the radioactivity concentration of normal air amounts to approximately 30 to 50 Bq/m^3 of ^{222}Rn). Aerosols with attached radon daughters are also found in the cigarette ash, as previously exhaled air is later inhaled through the cigarette. Again mainly the radioisotopes ^{210}Po and ^{210}Pb are found in the ash. This can be confirmed by an accurate gamma-ray spectroscopy of the cigarette ash. These isotopes are also found in the lungs and the bronchial tubes of smokers. The lead isotope ^{210}Pb, with a half-life of 22 years, continuously produces the dangerous alpha-ray emitter ^{210}Po via β^- decay. Therefore, the risk of developing lung cancer is relatively high even for people who have given up smoking. Some experts believe that the majority of cases of lung and bronchial cancer can be traced back to radioactivity and only to a lesser extent to tar and nicotine in the tobacco leaves.

A detailed analysis using gamma-ray spectroscopy with high-purity germanium counters shows that apart from the radioisotopes ^{238}U, ^{226}Ra, ^{232}Th, ^{210}Pb, and ^{210}Po, tobacco ash also contains ^{40}K. The specific radioactivity in tobacco and in tobacco ash varies widely depending on the choice of tobacco. As a typical result for the specific activity of cigarette ash, a value of 2000 Bq/kg can be given.

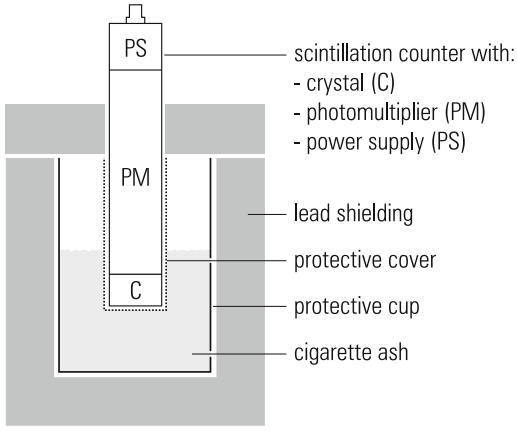


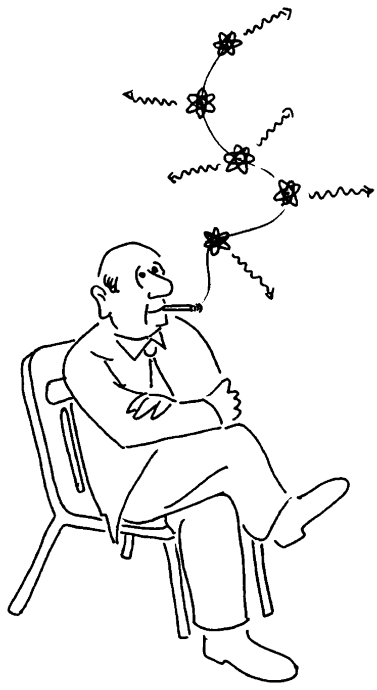
Figure 11.11
Measurement of the absolute activity of cigarette ash with a shielded scintillation counter

mated for people living in Western Europe to be on the order of $\leq$ 4 mSv.

smoking

Finally, in this chapter the aspect of exposures due to smoking shall be discussed. Radioactive isotopes like lead (^{210}Pb) enter the tobacco plant via its root from the soil, also radon (^{222}Rn) will enter the tobacco leaves from the air. This leads to relatively high exposures of the bronchi and the lungs. The isotopes ^{210}Pb and ^{222}Rn decay after a number of radioactive transmutations into the radioisotope polonium (^{210}Po) ending eventually in stable lead (^{206}Pb). The isotopes mentioned and their decay products have a certain affinity to attach to aerosols produced by the smoker. These contaminated aerosols are inhaled and some of them will stick on the surface of the lung of a smoker which is usually covered with traces of tar. As a consequence only part of the contaminated aerosols is exhaled. Values in the literature on the radiation exposure of bronchi and lungs of smokers differ quite substantially. They span a range of 0.05 up to several Sv for the bronchi in 25 years of smoking (1 packet of cigarettes per day). If this dose is translated into an equivalent whole-body dose, this will lead to an additional exposure

radioactive aerosols



"I do like to smoke!"

for a smoker on the order of 1 mSv/yr.[9] The polonium content of tobacco varies considerably so that the values given represent only a very rough estimation. There is, however, agreement among physicians that the additional radioactive exposure of the lungs for smokers eventually may lead to cancer of the bronchi and the lungs. This effect has been clearly established for smokers who work in uranium mines. For these miners a substantially elevated risk for lung cancer compared to non-smokers has been demonstrated. Also cancer of the throat is suspected to be caused by smoking. Obviously the combined effect of tar, nicotine, and exposure to radiation has quite negative consequences. Some scientists comment that smokers manage to combine the negative effects of chemical substances in the cigarette with the cancer-inducing properties of the ionizing radiation of isotopes in the tobacco leaves.

polonium content of tobacco

cancer of the bronchi and the lungs

The total average radiation exposure due to the technical environment is compiled in Table 11.2.

medicine, X-ray diagnostics[10]	$\approx$	1.9 mSv
nuclear medicine	$\approx$	0.05 mSv
science and research	$\leq$	0.01 mSv
occupational exposure	$\approx$	0.03 mSv
reactor accident in Chernobyl (only 1986)[11]	$\approx$	0.5 mSv
sum (without Chernobyl)	$\approx$	2.0 mSv

Table 11.2
Annual per capita radiation exposure (whole-body radiation, smoking not considered) due to radiation from technical installations

Figure 11.12 shows the different contributions of radiation exposure due to the technical environment in graphical form. Occupa-

total exposures

[9] In the literature one finds numbers for the equivalent dose between 5 nSv per cigarette and 40 µSv per cigarette. Some authors quote exposures for strong smokers of 40–400 mSv per year. Such high values can obviously be obtained if the tobacco plants are grown on soil with high concentrations of ^{210}Pb and ^{210}Po, for example, in certain areas of Brazil and Rhodesia (now Zimbabwe).

[10] The radiation exposure due to medical examinations varies quite considerably by country. It has to be noted that this exposure has increased over the last few decades. Some experts complain that too many X-ray images are taken. Several thousand tumors in patients are created annually by unnecessary X-ray examinations. Mammography screening with X rays for women of all age groups and frequent whole-body computer tomography as early detection method for cancer are also highly questionable.

[11] The number given is a rough estimate for the population in Western Europe. The Chernobyl plume was distributed over the whole northern hemisphere and could also be detected in the United States and in Japan. However, the exposures there were very low.

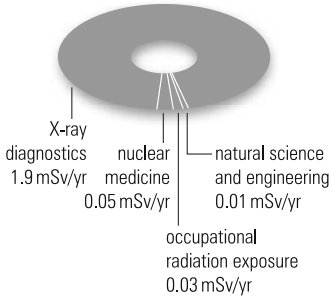


Figure 11.12
Different contributions to radiation exposure due to technical installations

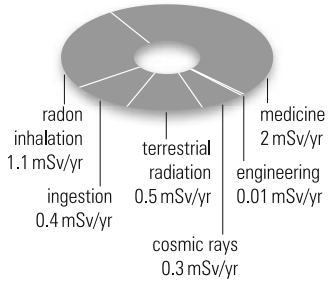


Figure 11.13
Different contributions to the total average per capita radiation exposure

Table 11.3
Typical dose rates or doses for some exposures (whole-body doses)

type of exposure	dose/dose rate
X-ray exposure of teeth	10 µSv
air flight Frankfurt – New York	30 µSv
X-ray examination of the chest	100 µSv
dose limit for normal population by discharges from nuclear power plants	300 µSv/yr
normal smoker	500 µSv/yr
mammography	500 µSv
gamma-ray image of the thyroid gland	800 µSv
limit for a surveyed area	1 mSv/yr
heavy smoker	1 mSv/yr
natural radiation	2.3 mSv/yr
lower limit for a controlled area (cat. A)	6 mSv/yr
positron-emission tomography	8 mSv
computer tomography of the chest	10 mSv
limit for radiation-exposed workers in Europe	20 mSv/yr
limit for radiation-exposed workers in the United States	50 mSv/yr
limit for emergencies	50 mSv
maximum dose over the whole life span	400 mSv
lethal dose	4000 mSv

typical radiation exposures

tional radiation exposure (for physicians, from nuclear technology, or at accelerators, ...) represents only a relatively small fraction compared to the exposures from medical diagnostics and therapy.

The world average of the whole-body exposure can be estimated to be about 4.3 mSv/yr (2.3 mSv/yr from the natural environment, 2.0 mSv/yr from technical installations (mainly medicine), see Fig. 11.13).

Table 11.3 gives an overview of typical radiation exposures.

natural radiation sources

One has to consider that radiation exposures from natural sources can be quite substantial. In terms of the biological effects, there is no difference between ionizing radiation from natural sources and that from technical installations.

Flying personnel are also subject to radiation monitoring, if the exposures exceed a value of 1 mSv/yr. This limit is reached after

only 200 flight hours at standard altitudes in the atmosphere. It goes without saying that the exposure should never exceed the limits given by the radiation-protection regulations, e.g. 20 mSv/yr in Europe.

In addition, it is important to consider exposures from elevated radon concentrations (mining) or in fields where uranium or thorium derivates are used (some welding electrodes and some incandescent mantles contain thorium). In any case a total dose of 400 mSv over the whole lifespan must not be exceeded.

Figure 11.14 shows the changes in the contributions to radiation exposure since 1940. The strong increase in radiation exposure due to medical examinations is quite remarkable. The radiation limit of 20 mSv/yr in European countries for radiation-exposed workers is actually quite close to the upper limit of the fluctuations of natural environmental radioactivity.

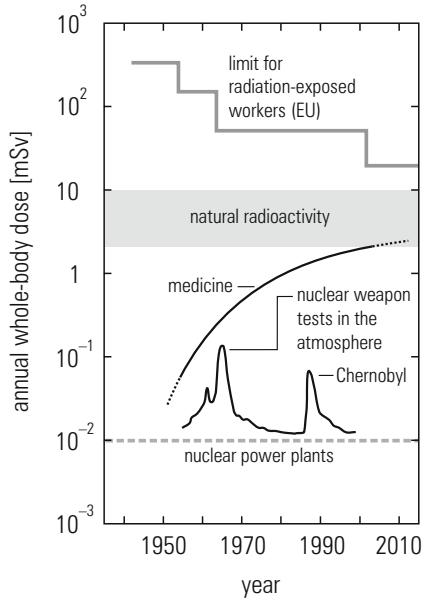


Figure 11.14
Comparison of radiation from the natural environment, exposures from nuclear medicine, legal limits, and exposures from nuclear weapon tests in the atmosphere and from the Chernobyl accident

11.5 Supplementary Information

Example 1

radon contamination of ground water and sea water

Sea water contains 0.01 Bq/l of radon while ground water exhibits radon concentrations of 100 Bq/l. Why?

As the name indicates, ground water originates from the Earth's crust. The Earth's crust and the rocks contain small concentrations

of the radioisotopes uranium, radium, and thorium. In the decay chains of these isotopes, the radioactive noble gas radon occurs. This is washed out by the ground water leading to an elevated radon concentration. In sea water the radon concentration is diluted to a large extent. Also, on average, sea water is separated from the bottom of the sea by a larger distance.

Sea water also contains a substantial amount of salt. This salt occurs in the from of sodium chloride and potassium chloride. Therefore, the sea water contains also the radioactive ^{40}K isotope leading to an activity of about 12 Bq/l. In contrast, this isotope occurs in ground water only with a concentration of about 0.1 Bq/l.

radon in rainwater

Rainwater can also wash out uranium, radium, and thorium from weathered rocks. These natural isotopes enter into the rainwater and also into the ground water, and via rivers they also reach the ocean. It is important to note, in particular, that the radon content in rainwater can be quite considerable.

Example 2

radiation exposure in flights

Radiation exposure during flights has already been discussed quite extensively in this chapter. In particular, the flight personnel themselves pointed out in the past that there is a possible hazard which might even be comparable to exposures in nuclear power plants.

Inside jets flying at a typical altitude of about 10–12 km, a dose rate of about 5 µSv/h is normally measured. For a crossing of the northern Atlantic from Frankfurt to New York (6 hours flight time), one obtains an integrated dose of 30 µSv. A flight from Frankfurt to Tokyo via India corresponds to approximately 60 µSv. Because of the dependence of the radiation exposure on the geomagnetic latitude a flight Frankfurt–Tokyo via the polar route (Alaska) would lead to an exposure of about 100 µSv.[12] A flight Frankfurt–Tokyo via the polar route by high-altitude aircraft (e.g. like with the former French Concorde (flight altitude 18–20 km)) resulted in even higher exposures. This was, however, partially compensated by the shorter flight time. Unusual solar activity during the flight led to an increased radiation. If the radiation level was too high, Concorde descended to below 14 km.

radiation exposure for flying personnel

Personnel flying at altitudes of 10–12 km are exposed to an annual dose of 2.5 mSv (for 500 flight hours per year). Pilots on high-flying research planes receive such a dose in only 125 flight hours. That is to say, flying personnel are working in a radiation-exposed

[12] At the poles charged particles of cosmic rays can penetrate much deeper into the atmosphere because their flight direction is parallel to the magnetic field lines (see also Footnote 1 on page 170). Apart from an elevated radiation exposure at the poles, the low-energy solar particles create fantastic polar lights (aurora borealis and aurora australis).

area and the dose rates received should be monitored by suitable equipment.

Example 3

Directly after the discovery of radioactivity it was suggested that ionizing radiation possesses healing powers. For example, in France a radioactive hair lotion was put on the market and the producer recommended its use with the following advertizement:

radioactive hair lotion?

The most wonderful discovery of the century
radium lotion 'Rezall'.
For the preservation of the hair,
no loss of hair,
no baldheadedness,
no more gray hair!

This advertizement is quite paradoxical, in particular, when one considers that the application of radioactive hair lotion actually leads to the loss of hair.

radioactive toothpaste?

In Germany a radioactive biologically effective toothpaste with the name DORAMAD was advertized. The ionizing radiation originating from this toothpaste – according to the advertizement – was supposed to massage the gums and refresh the whole mouth.

Thorotrast ®

Even up to the fifties of the last century a thorium-containing contrast agent with the name Thorotrast ® for the examination of the stomach and the intestine was used. The ThO_2 contained in the Thorotrast is predominantly stored in the liver and may lead to cancer of the liver and to liver cirrhosis.

radium-containing foot rests

Along similar lines, in the 1950s shops selling shoes provided a special X-ray device to test whether the shoes actually fit well. Also radium-containing foot rests with the brand name Elastosan were recommended as major improvement in modern chiropody. This radioactive foot rests exhibited a surface-dose rate of 2.5 µSv/h, comparable with exposures for flights in northern latitudes.

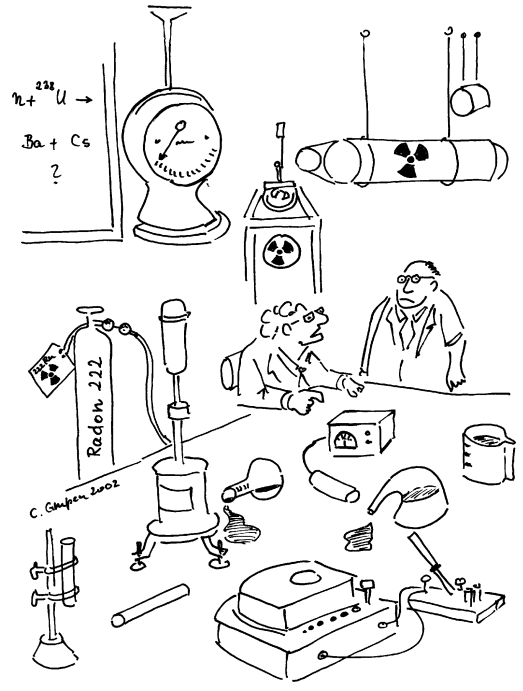
"DORAMAD preserves your teeth!!"
© by Claus Grupen

radioactive electric blankets

Even radium compresses were advertized in the period from 1920 to 1960 as an attractive alternative to electric blankets. According to the producer such a radium compress contained a guaranteed amount of at least 100 µg ^{226}Ra corresponding to an activity of 3.7 MBq. This is clearly above the exemption limit for this isotope. The γ-dose rate of such a compress resulted in a dose rate of 300 µSv/h even at a distance of one meter! They also promoted and advertized the ease of use of this activator blanket and pointed out that absolutely no danger is related to the use of this device. Press reports at the time also certified that for proper use and application of this highly concentrated radium compresses, there was no risk of harm.

radon treatment in baths

In this context, treatments like radon inhalations and drinking radium-containing water should also be mentioned. In the mines of Badgastein, a spa in Austria, the radon concentration was as high as 150 000 Bq/m^3. It has been reported that a research assistant of Otto Hahn, the discoverer of nuclear fission, was worried about the



"Why do you complain? You should be grateful!
In a spa you would be charged a lot of money for it.
Here you get it for free!"

inhalation and incorporation of radon and radioactive dust in his laboratories. When he pointed out this possible hazard to Hahn, Hahn was supposed to have said: Don't worry about that; other people pay a lot of money to go to Badgastein and you will get this radon inhalation here for free!

Summary

Radiation from the natural environment consists of, in roughly equal parts, cosmic rays, radiation from the ground (terrestrial radiation), and the incorporation of radioisotopes from the natural biosphere. The exposure due to technical equipment and installations has its origin almost exclusively in medicine (diagnosis and therapy). There is no difference between ionizing radiation from natural sources and ionizing radiation from technical installations.

11.6 Problems

Problem 1

The main radioisotopes in natural geological formations and in the Earth's crust are ^{40}K, ^{226}Ra, and ^{232}Th. The specific activity of normal ground is around 500 Bq/kg. Estimate the dose rate that originates from 1000 kg of soil at a distance of 1 m!

Problem 2

How does a four-week holiday at mountain altitudes (3000 m) compare to the exposure by an X-ray chest examination?

Problem 3

The personnel accompanying CASTOR transports is exposed to maximum dose rates of 30 µSv/h. How does the dose received for the accompaniment of a CASTOR transport over a time span of 10 hours compare with the annual radiation exposure in the Black Forest?