9. Radiation and the Environment

Biological Effects of Ionising Radiation

When ionising radiation passes through tissue, the component atoms may be ionised or excited. As a result the structure of molecules may change and result in damage to the cell. In particular, the genetic material of the cell, the DNA (deoxyribonic acid) may be changed. Two categories of radiation-induced injury are recognised: deterministic effects and stochastic effects. Deterministic effects are usually associated with high doses and are characterised by a threshold. Above this threshold the damage increases with dose. Stochastic effects are associated with lower doses and have no threshold. The main stochastic effect is cancer.

The radiation dose depends on the intensity, energy and type of the radiation, the exposure time, the area exposed and the depth of energy deposition. Various quantities such as the absorbed dose, the equivalent dose and the effective dose have been introduced to specify the dose received and the biological effectiveness of that dose [1].

Absorbed Dose

The absorbed dose (D) is the amount of radiation absorbed per unit mass of material. The modern SI unit of absorbed dose is the gray (Gy) where one gray is one joule per kilogram $1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$. In dosimetry, it is useful to define an average dose for a tissue or organ D_T. The absorbed dose to the mass δm_T, is defined as the imparted energy δE_T per unit mass of the tissue or organ, i.e.

$$D_\mathrm{T} = \frac{\delta E_\mathrm{T}}{\delta m_\mathrm{T}}\,.$$

The absorbed dose rate is the rate at which an absorbed dose is received. The units are $\mathrm{Gy\,s^{-1}}$, $\mathrm{mGy\,hr^{-1}}$, etc. Biological effects depend not only on the total dose to the tissue but also on the rate at which this dose was received. In organisms, mechanisms exist which enable molecules such as deoxyribonucleic acid (DNA) to recover if they have not been too badly damaged. Hence it is possible for organs to recover from a potentially lethal dose provided that the dose was supplied at a sufficiently slow rate. This phenomena can be exploited in cancer radiotherapy.

Quality or Weighting Factor

The biological effect of radiation is not directly proportional to the energy deposited by radiation in an organism. It depends, in addition, on the way in which the energy is deposited along the path of the radiation, and this in turn depends on the type of radiation and its energy. Thus the biological effect of the radiation increases with the linear energy transfer (LET) defined as the mean energy deposited per unit path length in the absorbing material (units keV μm^{-1}). Thus for the same absorbed dose, the biological effect from high LET radiation such as α particles or neutrons is much greater than that from low LET radiation such as β or γ rays. The quality or weighting factor, w_R, is introduced to account for this difference in the biological effects of different types of radiation. The weighting factors for the various types of radiation and energies is given in Table 9.1.

Table 9.1. The ICRP radiation weighting factors [2]

Type of radiation, R	Energy range	Quality or weighting factor, w_R
Photons, electrons	All energies	1
Neutrons	<10 keV	5
	10–100 keV	10
	100 keV–2 MeV	20
	2–20 MeV	10
	>20 MeV	5
Protons	<20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

Equivalent Dose, H_T

To reflect the damage done in biological systems from different types of radiation, the equivalent dose is used. It is defined in terms of the absorbed dose multiplied by a weighting factor which depends on the type of radiation i.e.

$$H_{T,R} = w_R D_{T,R} ,$$

where $H_{T,R}$ is the equivalent dose in tissue T and w_R is the radiation weighting factor. The ICRP weighting factors are given in Table 9.1.

Equal equivalent doses from different sources of radiation delivered to a point in the body should produce approximately the same biological effect. However, a given equivalent dose will in general produce different effects in different parts of the body. A dose to the hand is, for example, considerably less serious than the same dose to blood forming organs. If there are several types of radiation present, then the equivalent dose is the weighted sum over all contributions, i.e.

$$H_T = \sum_R \left(w_R D_{T,R} \right) .$$

The SI unit of dose is the Sievert, Sv (1 Sv = 1 J kg^{-1}, the old unit is the rem, 1 Sv = 100 rem). This is the equivalent dose arising from an absorbed dose of 1 Gy. Hence

for γ rays, where $w_R = 1$, an absorbed dose of 1 Gy gives an equivalent dose of 1 Sv. The same absorbed dose for α particles, where $w_R = 20$, gives an equivalent dose of 20 Sv. The equivalent dose rate is the rate at which an equivalent dose is received, i.e.

$$dH_{T,R}/dt = w_R dD_{T,R}/dt \ .$$

The equivalent dose rate is expressed in Sv s^{-1} or mSv hr^{-1}.

The sievert, Sv, is the unit describing the biological effect of radiation deposited in an organism. The biological effect of radiation is not just directly proportional to the energy absorbed in the organism but also by a factor describing the *quality* of the radiation. An energy deposition of 6 J per kg due to gamma radiation (quality = 1), i.e. 6 Sv is lethal. This same energy deposited in the form of heat (quality = 0) will only increase the body temperature by 1 mK and is therefore completely harmless. The difference between the two types of radiation is due to the fact that biological damage arises from ionisation.

Effective Dose, *E*

In general, cells which undergo frequent cell divisions, and organs and tissue in which cells are replaced slowly, exhibit high radiation sensitivity. This is why different tissues show different sensitivities to radiation. The thyroid, for example, is much less sensitive than bone marrow. In order to take these effects into account, equivalent doses in different tissues must be weighted. The resulting effective dose is obtained using

$$E = \sum_T (w_T H_T) \ ,$$

where H_T is the equivalent dose in tissue or organ T and w_T is the tissue weighting factor. The ICRP tissue weighting factors are shown in Table 9.2.

Table 9.2. ICRP Tissue weighting factors [2]

Tissue	Weighting factors, w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Committed Effective Dose, $E(\tau)$

A person irradiated by gamma radiation outside the body will receive a dose only during the period of irradiation. However, following an intake by ingestion or inhalation, some radionuclides persist in the body and irradiate the various tissues for many years. The total radiation dose in such cases depends on the half-life of the radionuclide, its distribution in the body, and the rate at which it is expelled from the body. Detailed mathematical models allow the dose to be calculated for each year following intake. The resulting total effective dose delivered over a lifetime (70 years for infants, 50 y for adults) is called the committed effective dose. The name arises from the fact that once a radionuclide has been taken up into the body, the person is "committed" to receiving the dose [1]. The ICRP has published values for committed doses following intake of 1 Bq of radionuclide via ingestion and inhalation. These are known as the effective dose coefficients $e(\tau)$ and have been calculated for intake by members of the public at six standard ages, and for intake by adult workers. The unit of the effective dose coefficient is Sv/Bq.

Collective Effective Dose

On the assumption that radiation effects are directly proportional to the radiation dose without a threshold, then the sum of all doses to all individuals in a population is the collective effective dose with unit manSv. As an example, in a population consisting of 10,000 persons, each receives a dose of 0.1 mSv. The collective dose is the $10\,000 \times 0.0001 = 1$ manSv. The effects of various doses to man are listed in Table 9.3.

Table 9.3. Effects of radiation exposure to man [3]

Dose (whole body irradiation)	Effects
< 0.25 Sv	No clinically recognizable damage
0.25 Sv	Decrease in white blood cells
0.5 Sv	Increasing destruction of the leukocyte-forming organs (causing decreasing resistance to infection)
1 Sv	Marked changes in the blood picture (decrease in the leukocytes and neutrophils)
2 Sv	Nausea and other symptoms
5 Sv	Damage to the gastrointestinal tract causing bleeding and ≈ 50% death
10 Sv	Destruction of the neurological system and ≈ 100% death within 24 h

Radiotoxicity and Annual Limits of Intake

Radiotoxicity of an isotope refers to its potential capacity to cause damage to living tissue as the result of being deposited inside the body. This damage potential is

Committed Effective Dose, $E(\tau)$

The sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors (w_T), where τ is the integration time in years following the intake. The integration time for adults is 50 years.

Effective Dose Coefficient, $e(\tau)$

The committed effective dose per unit acute intake where τ is the time period in years over which the dose is calculated (e.g. $e(50)$).

Intake

Activity that enters the respiratory or gastrointestinal tract from the environment.

governed by the type and energy of the radioactive disintegration, the physical half-life, the rate at which the body excretes the material, and the radio-sensitivity of the critical organ.

The radiotoxicity is defined here in terms of dose received by a population ingesting all the radioactive materials present at a given time, taking into account the nature and energy of the emitted radiation and its effect on biological organisms. For this purpose it is suitable to use the Committed Effective Dose $E(\tau)$ – see inset – as a measure of the radiotoxicity, hence

$$\text{Radiotoxicity} = E(\tau)\,.$$

The committed effective dose of a radionuclide is given by the effective dose coefficient multiplied by the activity of the radionuclide at the time of intake, hence

$$\text{Radiotoxicity} = A \cdot e(\tau)\,,$$

where A is the activity of the radionuclide at the moment of intake.

It should be noted that many radionuclides decay to nuclides that are themselves radioactive (radioactive daughters). The effective dose coefficients take into account the ingrowth of daughters in all regions of the body following an intake of unit activity of the parent nuclide. They do not take into account any activity of daughter nuclides in the initial intake.

The activity is just the number of disintegrations per second and is measured in units of becquerel, Bq (1 Bq = 1 disintegration per second). The effective dose coefficient e is a measure of the damage done by ionising radiation associated with the radioactivity of an isotope. It accounts for radiation and tissue weighting factors, metabolic and biokinetic information. It is measured in units of sievert per becquerel (Sv/Bq) where the sievert is a measure of the dose arising from the ionisation energy absorbed.

The Annual Limit of Intake (ALI) of an isotope is defined as the activity required to give a particular annual dose. Publication 60 of the ICRP recommends a committed effective dose limit of 20 mSv per year, hence

$$ALI = \frac{(0.02)\,\text{Sv}}{e(50)}\,.$$

The *ALI* is a calculated value based on the primary dose limit and gives only the annual limit of intake. It is sometimes more useful to establish the limits on the concentration of a radionuclide in air or water which would lead to this intake. For this purpose the derived air concentration (*DAC*) is introduced for airborne contaminants. The *DAC* is the average atmospheric concentration of the radionuclide which would lead to the *ALI* in a reference person as a consequence of exposure at the *DAC* for a 2000 h working year. A reference person inhales 20 litres of air per minute or 2400 m^3 during the working year. The derived air concentration is

$$DAC\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right) = \frac{ALI_{\mathrm{inh}}(\mathrm{Bq})}{2400\,\mathrm{m}^3}\,.$$

^{137}Cs, for example, has an $ALI_{\mathrm{inh}} = 3.0 \times 10^6$ Bq. It follows that the *DAC* = 1.2 Bq/m^3. Similarly the derived water concentration (*DWC*) is given by

$$DWC\left(\frac{\mathrm{Bq}}{\mathrm{litre}}\right) = \frac{ALI_{\mathrm{ing}}(\mathrm{Bq})}{913\,\mathrm{litre}}$$

based on a water intake of 2.5 litre per day. For members of the public, the values obtained for the *DAC* and *DWC* should be further reduced by a factor 20 corresponding to a dose limit of 1 mSv per year.

Table 9.4. Annual Limits of Intake (*ALI*) for ingestion which results in a dose of 0.02 Sv for the main radioactive by-products of nuclear waste. The values are given in both becquerel and mass units

Isotope	Annual Limit of Intake (becquerel)	Annual Limit of Intake (mass)
Plutonium-239	8.0×10^4	30 μg
Minor actinides MA		
Neptunium-237	1.82×10^5	7 mg
Americium-241	1.00×10^5	0.8 μg
Curium-244	1.67×10^5	0.06 μg
Selected fission fragments		
Technetium-99	3.13×10^7	40 mg
Iodine-129	1.82×10^5	30 mg
Caesium-135	1.00×10^7	0.2 g

Radiation Hormesis and the Linear Non-Threshold (LNT) Model

Although it is generally believed that low doses arising from chemicals, pharmaceuticals, radiation, etc. produce effects proportional to high doses, there is evidence to suggest that this is incorrect and that low doses may have a beneficial effect to biolog-

ical systems. This positive effect arising from low doses is referred to as "hormesis" from the Greek word "hormaein" which means "to excite". Radiation hormesis refers to the stimulation of biological functions by low doses of radiation.

The first observation of hormesis dates to the 1940s where it was reported that low doses of Oak bark extract stimulated fungi growth (in contrast to inhibiting growth at high doses). In the 1980s, the first complete report on radiation hormesis was published [4].

Toxicology, and in particular the dose response relation, is very important in many medical and public-health issues. Predictions based on this relationship have major implications for risk assessment and risk communication to the public. At issue here is the known hormetic (beneficial or positive) response of cells and organisms to radiation dose.

It has been claimed recently [5] that the toxicological models in current use by regulatory authorities to extrapolate dose response at low doses of carcinogens are incorrect. Traditionally, the dose-response relationship used for risk assessment to obtain the risk from low doses of carcinogens is the so-called "linear non-threshold model" (LNT) shown in Fig. 9.1b. There is increasing evidence, however, that the dose-response relation is actually "U" shaped or "J" shaped as shown in Fig. 9.1c. This "U" shape is a manifestation of hormesis where a response stimulation occurs at low doses.

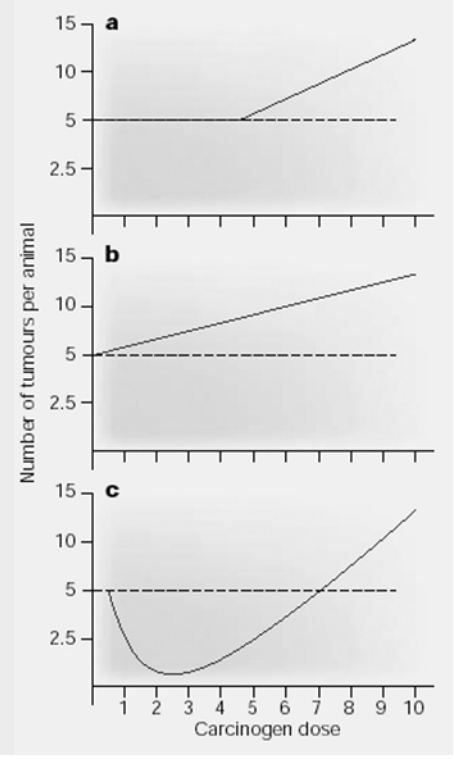


Fig. 9.1. Hypothetical curves depicting (**a**) threshold, (**b**) linear non-threshold, and (**c**) hormetic dose-response models using cancer (number of tumours per animal) as the endpoint. The reduction in number of tumours per animal at the lower doses (1–6) compared to the number of tumours per animal (5 tumours per animal) in the control indicates a reduced risk of cancer. (Reprinted by permission from Nature [5]. © 2003 Macmillan Publishers Ltd.)

Current radiation protection standards are based on the assumption that all doses, no matter how small, can result in health detriment and the likelihood is directly proportional to dose received; i.e. the accepted dose response relationship for estimating harm is the linear non-threshold (LNT) model. According to the Health Physics Society, there is increasing scientific evidence that this model represents an oversimplification of the biological mechanisms involved and that it results in an overestimation of health risks in the low dose range. The Health Physics Society notes that radiogenic health effects (primarily excess cancers) are observed in human epidemiology studies only at doses in excess of 0.1 Sv delivered at high dose rates. Below this dose, estimation of adverse health effects is speculative.

UNSCEAR is also showing increasing reservation toward the use of dose commitment (individual dose integrated over infinite time) and collective dose. Both are consequences of the linear non-threshold model of radiation effects. Recent radiobiological and epidemiological studies suggest that this model has lost credibility [6]. The organisation is proposing to spend more time and resources to learn the effect of anthropogenic radiation on individual plants and animals. It is well known, for example, that in Kerala, India, where the natural radiation level (up to about 400 millisieverts per year) is much higher than the average global one (2.4 mSv), black rats for 800 to 1000 generations have shown no adverse biological effects [6, 7].

High Background Radiation Areas Around the World

According to the UNSCEAR 2000 report, in the seaside city of Guarapari (80,000 inhabitants), Brazil, peak dose rate measurements on the beach are as high as 40 μSv/h – about 200 times higher than the average natural background radiation level in other areas of the world. In Ramsar, northern Iran, some inhabited areas have the highest known natural radiation levels (up to 260 mSv/y) [7].The radiation in Ramsar is due primarily to radium dissolved in mineral water.

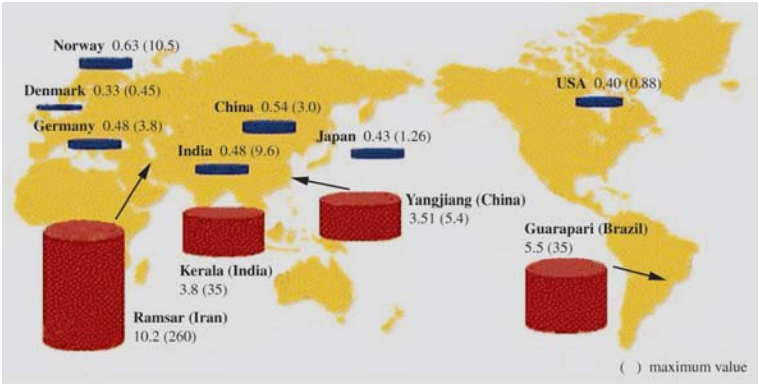


Fig. 9.2. Average (and maximum) dose rates in mSv/y worldwide. Figure adapted from Health Research Foundation, Kyoto, Japan. With courtesy to S. M. Javad Mortazavi, Biology Division, Kyoto University of Education, Kyoto, Japan

Radon: A Test for the LNT Hypothesis?

What is Radon?

Radon (^{222}Rn) is a colourless, odourless, tasteless, radioactive noble gas which occurs naturally from the decay of uranium in the earth. It arises from the radioactive decay of ^{226}Ra (itself a decay product of uranium) and has a half-life of 3.8 days. Its short-lived daughter products include the alpha emitters ^{210,214,218}Po.

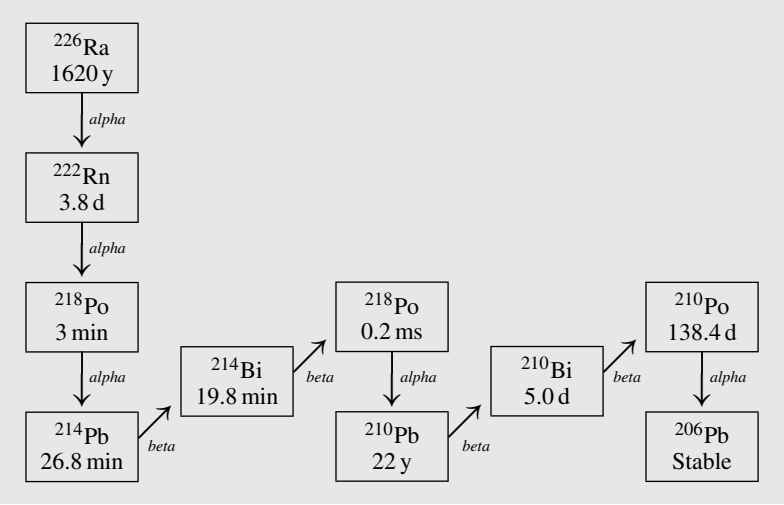


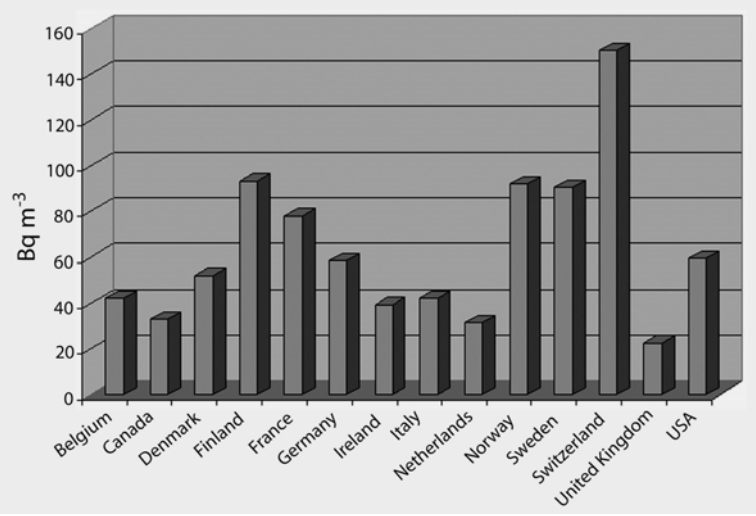
Fig. 9.3. Decay chain of ^{226}Ra

Radon gas can be found where uranium is present in the ground. The gas concentration builds up in caves and in the cellars of buildings. Of the naturally ocurring radiation sources giving rise to a total radiation dose of 2.4 mSv/y, radon gas is the largest contributor with a value of 1.3 mSv/y [8]. It has been estimated that between 5% and 15% of all lung cancer cases are attributed to radon inhalation.

For centuries, it has been known that some underground miners suffered from higher rates of lung cancer than the general population. The link between ^{222}Rn exposure and lung cancer was first postulated in 1556 when Agricola described high mortality rates among underground miners in the Erz Mountains of Central Europe. Since then many studies of miners have confirmed this link. In the 1950s, the cause of lung cancer was attributed to the radon progeny (the daughters of ^{222}Rn). These radioactive daughters are electrically charged and can attach themselves to tiny dust particles in indoor air. Particles inhaled adhere to the lung linings where they cause radiation damage to the cells by disrupting the cell DNA whch can eventually lead to cancer.

In 1998 the National Academy of Sciences (NAS) estimated that between 3000–32,000 lung cancers deaths per year in the U.S. are attributable to to residential ^{222}Rn progeny [9]. The authors, however, cautioned that there is considerable uncertainty

Table 9.5. Average concentration of radon in Europa and North America: Exposure to radiation from natural sources can be significant. The radon in the domestic environment can give rise to annual doses that exceed the ICRP dose limits for occupational exposure. A value of 50 Bq/m^3 corresponds to an averaged equivalent dose of 15 mSv/y



in these figures because of limited knowledge on the effects of low levels of exposure and that from the evidence now available, a threshold exposure, that is, a level of exposure below which there is no effect of radon, cannot be excluded.

Current EU limit is 200 Bq/m^3 for new and 400 Bq/m^3 for old houses. These values, however, are exceeded in many countries. The ICRP suggests 500 Bq/m^3 for homes and 1000 Bq/m^3 for the workplace [10].

Therapeutic Effects of Radon

Observations of the beneficial effects of radon on human health date back to prehistoric times [11]. There is archaeological evidence that radon sources were in use in Gastein, Austria thousands of years ago. The ancient Romans used radon spas and in Ischia, Italy, the therapetic baths have been in use for over 2000 years. The springs of Misasa in Japan have been in use for 800 years.

Today there are many therapeutic radon centres in use: in Germany, in Austria (most well known is Bad Gastein, Fig. 9.4), Czech Republic, France, Italy, Ukraine, Russia, Japan, and the U.S. Currently some 75,000 patients are treated annually in German and Austrian radon spas mostly for painful inflamatory joint diseases such as rheumatism, arthritic problems, Morbus Bechterew, psoriasis, gout, chronic bronchitis, asthma etc.

Following a three week treatment period, beneficial effects are claimed to last for periods of six months or more. Treatment involves inhaling radon in high concentration. In Bad Gastein's Heilstollen the radon concentration is 170,000 Bq/m^3 (almost

Fig. 9.4. Therapy zone in Bad Gastein (Austria) healing gallery

a thousand times higher than the current legilsation) or by drinking or bathing in radon water.

In view of the claimed contribution to the population dose and the associated risk of lung cancer (indoor radon claimed to cause about 20,000 lung cancer deaths annually in the U.S.) it is suprising to note that the costs for the radon therapy are partly covered by the medical health insurance schemes.

A Test for LNT?

Because of the claimed large contribution to the total population dose, the effects of radon should be considered as a test for the validity of the LNT hypothesis. It has, for example, been claimed recently [11] that radon studies provide evidence against the LNT hypothesis.

Radiation Exposure in High-Flying Aircraft

The radiation exposure to passengers and crew in high-flying aircraft is caused by energetic photons and particles such as neutrons, protons, electrons, muons, and pions. These radiation types are produced as a result of the interaction with the Earth's

Cosmic Rays

These comprise 85% protons, 14% alpha particles, and 1% heavier ions covering the full range of elements, some of the more abundant being, for example, carbon and iron nuclei. They are partly kept out by the earth's magnetic field and have easier access at the poles compared with the equator. From the point of view of space systems it is particles in the energy range 1–20 GeV per nucleon which have most influence.

atmosphere of high-energy particles (primarily protons and alpha particles) that come from a variety of cosmic sources in our galaxy, with a lesser contribution from our own sun. The galactic component of this incoming cosmic radiation is always present; the solar contribution varies in intensity over an approximately eleven-year cycle. In fact, the galactic component is greatest at solar minimum and is reduced at solar maximum by solar particle interactions with irregularities in the magnetic field associated with the "solar wind."

There are four main factors that affect the increased radiation dose received by travellers on long-distance airflights: altitude, latitude, hours aloft, and solar activity [12, 13].

Altitude

The amount of cosmic radiation doubles approximately with every 2000-metre increase in altitude. In most commercial aircraft, which fly at 10,000 or 12,000 metres, cosmic radiation is approximately 100 times higher than on the ground [13]. In flights on the Concorde at a height of 18,000 metres, passengers received a radiation dose twice as intense as on subsonic flights. However, since the flight time is shorter, the dose received during a flight is virtually identical to the one received during a subsonic flight on any given route.

Latitude

The Earth's magnetic field creates a barrier which causes cosmic radiation to be concentrated at high latitudes near to the north and south magnetic poles. The dose rate at 70 degrees north or south latitude is about four times as much as at 25 degrees [12]. Thus, flights over polar routes will result in higher radiation dose rates than those at lower latitudes.

Flight Duration

The total dose of cosmic radiation received is directly proportional to the duration of exposure, and thus with the duration of the flight. For occasional travellers, rather than frequent flyers, this increased radiation does not present a significant risk. Airplane crew, however, with 1000 hours flying time, would receive a dose in the range 5–10 mSv depending on the route.

Solar Activity

Solar flares can increase the cosmic radiation level. Unlike the stable radiation of galactic origin, the sun is the source of an unpredictable component of cosmic radiation. It constantly ejects particles with an intensity which varies according to an 11-year cycle as shown in Fig. 9.5.

Typical annual doses received by cabin personnel, frequent and occasional flyers are shown in Table 9.6. Further information on cosmic radiation and the calculation of the dose received in high-flying aircraft can be found at the SIEVERT website [13].

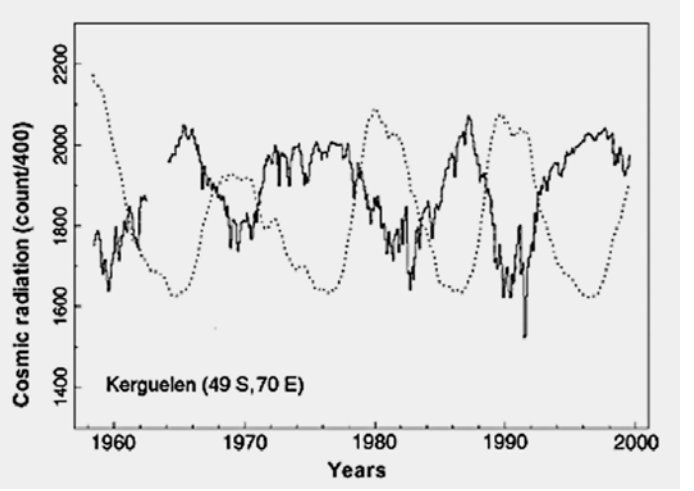


Fig. 9.5. Variation in the intensity of galactic cosmic radiation observed on the ground from 1959 to 2000, compared with that of the index of sunspots (dotted line). During periods of high solar activity, the cosmic radiation is less intense, as the particles have more difficulty reaching the Earth. Source: IPEV and Paris Observatory [13]

Table 9.6. Annual dose received in high-flying aircraft (based on a flying altitude of 10,000 m – at this height the radiation dose rate is 52 mSv/y, corresponding to 6 μSv/h) [11]

	Cabin personnel	Frequent flyers	Occasional flyers
Flight duration	40 days per year	10 days per year	2 days per year
Dose	$52 \cdot (40/365)$ $= 5.7$ mSv	$52 \cdot (10/365)$ $= 1.4$ mSv	$52 \cdot (2/365)$ $= 0.3$ mSv

In the recommendations of both the NCRP and ICRP, two population groups are identified i.e. members of the general public, and "radiation workers" who are exposed to radiation through their occupation. For this latter group, government standards give an occupational exposure limit which is 20 to 50 times greater than those for the general public (Table 9.7). The rationale for this distinction is that

Table 9.7. Maximum permissable doses (MPD) to radiation workers and members of the public

		NCRP	**ICRP**
General public:	Annual MPD	1 mSv	1 mSv
Radiation workers:	Annual MPD	50 mSv	20 mSv
	Cumulative MPD	10 mSv × age	–
	MPD during pregnancy	5 mSv	2 mSv

"radiation workers" presumably accept the increased risk in exchange for the benefits of employment. Note that in addition to its annual MPD for occupationally exposed radiation workers, the NCRP recommends a cumulative lifetime limit (in mSv) equal to 10 times a worker's age. So, for instance, a pilot who retires at age 60 should not be exposed to more than 600 mSv over his entire flying career. Assuming that career lasts 30 years, average annual exposure should not exceed 20 mSv.

Conan the Bacterium

The bacterium *Deinococcus radiodurans* or *D. radiodurans*, which means "strange berry that withstands radiation", was first identified in 1956. It was isolated from a can of beef which had been radiation sterilised. Normally bacteria do not withstand the radiation processing. This was not the case, however, with *D. radiodurans* now affectionately known among scientists as Conan the Bacterium [14, 15].

Not only does the bacterium show resistance to toxic chemicals, but *D. radiodurans* is extremely resistant to massive doses of ionising radiation. Following a radiation dose in excess of 10,000 Sv (thousands of times higher than the lethal radiation dose in humans), the radiation damaged the bacterium's genetic material by breaking each of the chromosomes into more than one hundred pieces. Due to a a unique repair system which efficiently repairs the damage to its DNA the bacterium returns to normal within a few hours.

The bacterium is believed to be as old as the Earth and could have been one of the earliest forms of life on the planet. Due to its radiation repair abilities it could even have come from space.

An interesting application is to use a genetic manipulation of the bacteria to break down toxic organic chemicals at radioactive waste sites. In particular, the task is to engineer radiation-resistant microbes that degrade or transform this waste into less hazardous forms. Using bacteria for such purposes is known as bioremediation. In the US, some 3000 sites have been contaminated due to nuclear related activities. In many of the sites, the waste contains a mixture of organic pollutants with radioisotopes of

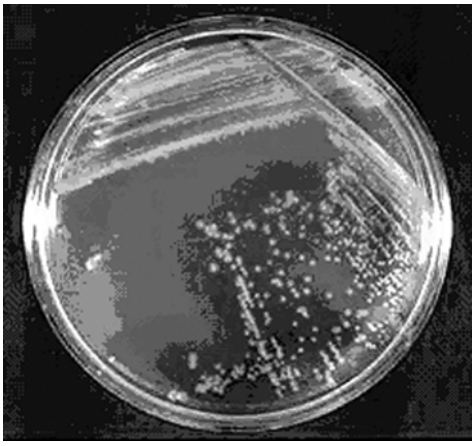


Fig. 9.6. Colonies of *D. radiodurans* growing in a petri dish.
Courtesy Michael Daly

uranium and plutonium. Traditional physicochemical cleaning methods would take decades and prove very costly. Bioremediation techniques could be considerably less expensive than the conventional methods.

Packaging and Transport of Radioactive Materials

Each year more than 10 million packages of radioactive materials are transported worldwide. Radionuclides are used for a variety of purposes e.g. in nuclear medicine, materials testing, oil exploration etc. For these purposes, radioactive materials must be packaged and transported to the location of interest. Before these materials can be shipped, care must be taken that the regulations have been strictly followed. The purpose of these regulations, of course, is to ensure safety by containing the radioactivity to make sure that there is no negative effect on the environment, to control the radiation emitted from the package, make sure that nuclear fission criticality conditions cannot be met, and to dissipate any heat generated within the package.

For the purpose of transportation, radioactive materials were previously defined as those materials which spontaneously emit ionising radiation and have a specific activity in excess of 0.002 microcuries per gram (0.002 μCi/g or 74 Bq/g) of material. In 2001, new regulations on the transport of radioactive materials were introduced with lower limits on the specific activity of individual nuclides [16].

The choice of packaging depends on the radionuclides involved, the amounts of radioactivity to be shipped and the form of the radionuclides. Restrictions on the amounts of material are determined by the so-called "$A1$" and "$A2$" values [16]. "$A1$" is the maximum amount of activity for a special form radionuclide that is allowed in Type A packaging, whereas "$A2$" refers to the maximum amount of activity in a Type A package for normal form materials. Usually the $A1$ or $A2$ values can not exceed 37 terabecquerels (37×10^{12} Bq) or 1000 curies (Ci). For some materials, however, the limits have been set to 40 TBq or more (in the case of ^{238}U).

Example. As an example, consider the radionuclides ^{137}Cs and ^{60}Co. The $A1$ and $A2$ values are shown in Table 9.8 where it can be seen that the values for ^{137}Cs are quite different and for ^{60}Co are the same.

Table 9.8. Maximum activities for special ($A1$) and normal form ($A2$) materials

Nuclide	$A1$ (special form)	$A2$ (normal form)
^{137}Cs	2 TBq	0.6 TBq
^{60}Co	0.4 TBq	0.4 TBq
^{238}U	No limit	No limit

In the case of ^{60}Co, this means that even if five different exposure pathways are considered, there is no greater risk than if only the external gamma radiation pathway were considered. This is not the case with ^{137}Cs which does indeed depend on the exposure pathway.

The special form referred to above refers to the fact that if the material were released from the package, the only hazard would be from external gamma radiation. An example of such a special form is that of a sealed (encapsulated) source of radiation. Here the durable metal capsule with high physical integrity ensures that the radioactivity will not disperse. In addition, only solid materials are classified as "special form". Special form encapsulation is designed such that the capsule cannot be opened unless it is destroyed.

In contrast to special form materials, normal form materials may be solid, liquid, or gaseous. Examples here are waste materials in a plastic bag, a liquid-containing bottle housed with a metal contained, powder in a glass or plastic bottle, contaminated soil in a drum, or gas in a cylinder.

A1

The values of the quantity $A1$ arise through worst-case assumptions with regard to external gamma radiation from a known source at a certain distance. More exactly, the $A1$ value for a particular radionuclide is that quantity of radionuclide which will give rise to a dose rate of 0.1 Sv/h at a distance of 1 m from the package. Since only external radiation is considered, it is assumed that the radioactive material inside the package will not be dispersed if the package is damaged.

A2

The $A2$ value also relates to the worst-case assumptions, but five different exposure pathways are considered rather than just the single pathway associated with the $A1$ value. The five pathways are:

- external gamma radiation
- external beta radiation to the skin
- inhalation
- ingestion
- external gamma radiation from immersion in a gaseous cloud of radioactive material released from a damaged package

It is important to note that the $A2$ values refer to normal form radioactive materials and to both external and internal exposure. In contrast to the $A1$ value, the $A2$ value assumes that dispersal and contamination of the package content is probable. On this basis, the $A2$ values are always lower than the $A1$ values.

Packaging

Type A packaging is required for shipping radioactive materials when the radioactivity inside the package does not exceed the $A1$ or $A2$ values. If the radioactivity is higher, type A packaging, which is foreseen for normal transportation conditions and minor accidents only, cannot be used. The basic purpose of type A packaging is to prevent loss or dispersal of the package contents while maintaining proper radiation shielding under normal transportation conditions. Type A packaging must withstand water spray, drop, puncture and crash tests.

When the level of radioactivity exceeds the $A1$ and $A2$ values, type B or type C packaging is required. Type B and C packaging must meet all the conditions of

type A packaging and in addition have the ability to withstand serious accidents. Examples of type B packaging are spent nuclear fuel casks.

Transport Index

The Transport Index "*TI*" is the dose rate in units of millisieverts per hour (mSv/h) at a distance of one meter from the external surface of a package containing radioactivity, multiplied by a factor 100. The Transport Index is printed on the label of a package so that interested persons can assess the relative radiation hazard and the control to be exercised upon handling. In special cases (tanks, big containers), an additional multiplication factor must be used.

Nuclear Waste Disposal

Nuclear waste disposal is a problem of radioactive material "packaging" in the extreme. One of the challenges facing the nuclear industry is to demonstrate that an underground repository can contain nuclear waste for very long periods of times and that any releases that might take place in the future will pose no significant health or environment risk. It must be taken into account that the engineered barriers which initially contain the wastes will degrade, and that some residual radionuclides may return to the surface in low concentrations at some time in the future due to groundwater movement and environmental change.

One way of building confidence in engineered barriers is by studying the processes which operate in natural and archaeological systems and by making appropriate parallels with a repository. These studies are called "natural analogues" [17]. The natural analogues are particularly relevant in the event that nuclear waste transmutation is introduced[1].

Natural Analogues

There are many radioactive materials which occur naturally and can be found in rocks, sediments etc. In particular, uranium which is the main component in nuclear fuel, occurs in nature. By studying the distribution in nature, information can be obtained on the movement of uranium in rocks and ground waters.

Natural analogues provide a way of informing the wider public on the principles on which repositories are built, without using complex mathematical demonstrations of "safety" and "risk". One of the concepts which can be presented using analogues is the very slow degradation of materials over thousands of years. Some notable natural analogues are:

[1] Recently proposals have been put forward to introduce transmutation of nuclear waste reduce the burden of underground repositories [18]. Through transmutation, the mass and the radiotoxicity of the waste are significantly reduced as is also the time needed to reach the radioactivity level in natural ores. The proposed schemes lead to the radiotoxicity of the waste reaching reference levels in about 500–700 years rather than hundreds of thousands of years in the natural decay process.

• **The Inchtuthil Roman Nails:** The most northerly fortress in the Roman Empire at Inchtuthill in Perthshire, Scotland had to be abandoned hastily in 87 AD. In an attempt to hide metal objects which could be used for weapons, the Romans buried over one million nails in a 5 m deep pit and covered them with 3 m of compacted earth. These nails were discovered in the 1950s.

Fig. 9.7. A Roman nail found at Inchtuthil, Scotland. © Glasgow Steel Nail Co. Ltd.

It was found that the outermost nails were badly corroded and had formed a solid iron oxide crust. The innermost nails, however, showed only very limited corrosion. This was attributed to the fact that the outer nails removed the oxygen from the infiltrating groundwater such that by the time they came into contact with the innerlying nails the waters were less corrosive. In the same way, the large volumes of iron in waste canisters are expected to maintain chemically reducing conditions in an environment which is oxygen rich due to the radiolytic decomposition of water.

• **The Kronan Cannon:** The Kronan was a Swedish warship built in 1668 and which sank in 1676 during the Battle of Öland [19]. One of the bronze cannon on board the Kronan had remained partly buried in a vertical position, muzzle down in clay sediments since the ship sank. This cannon is a good analogue for canisters to be used in the Swedish and Finnish spent fuel repositories which have a copper outer shell since the cannon had a very high content of copper (96.3%). From an analysis of the cannon surface, a corrosion rate of 0.15 μm/y was established. At this rate of corrosion, it would take some 70,000 years to corrode 1 cm thickness of copper. This provides evidence for the very long life of copper spent fuel canisters in the repository.

• **Hadrian's Wall:** In AD 122 Emperor Hadrian ordered construction of a wall to separate the lands of the Britons from that of the Picts to the north. Hadrian's Wall was over 100 km long and 5 m high and was built from stone blocks cemented together. The Wall is of interest as an analogue due to the longevity of Roman cement used to bind the stones together. Modern Portland cement is very similar chemically and mineralogically. From these studies, conclusions can be drawn with regard to the stability and longevity of modern cements in repositories.

• **The Dunarobba Forest:** In the Dunarobba forest near Todi in Italy, dead tree trunks approximately 2 million years old have been found in their original upright position [20]. Remarkably, in contrast to typical fossilised trees, the Dunarobba trees are still composed of wood. The wood has been preserved due to the surrounding clay. This clay stopped oxygenated waters reaching the wood thereby limiting the aerobic decomposition. The Dunarobba trees are of relevance in repository concepts since the wood is considered to be analogous to the organic/cellulosic materials which comprise a large part of the waste.

Fig. 9.8. The Dunarobba Forest, Italy. © CRIDEA (ref. 20)

• **The Needle's Eye:** This site in south-west Scotland, close to a natural rock arch known as the Needle's eye, comprises a sea-cliff in which the mineralised veins of uranium and other metals are partly exposed [21]. Uranium is present as pitchblende (UO_2) associated with secondary minerals.

Fig. 9.9. The Needle's Eye, Scotland. Courtesy Michael E. Brookfield

The pitchblende has undergone dissolution by two processes. In the first, slow leaching results in a preferential loss of ^{234}U relative to ^{238}U. The second is dissolution by oxidising waters. The mobilised uranium is redeposited in close proximity to the vein as stable oxidised uranium minerals. In contrast to uranium, the dissolution and transport of thorium is negligible.

The Needle's Eye is ideal for investigating radionuclide migration behaviour and for testing geochemical codes in simulation exercises.

• **The Oklo Natural Fission Reactors:** In 1972 scientists in France found that the ^{235}U content of ore being processed to make nuclear fuel pellets had been depleted from the normal 0.72% to 0.62%. The ore had been obtained from Oklo in the south-

east part of the Republic of Gabon in West Africa. Further investigations revealed that nuclear fission had taken place. The uranium ore bodies at Oklo are the only known examples of natural fission reactors. The criticality took place approximately 2 billion years ago as a result of dissolution, mobilisation and accumulation of uranium in sufficient mass to achieve criticality. Natural uranium had a much higher content of ^{235}U at that time. The chemistry of the uranium is such that it is practically insoluble in water under oxygen-free conditions, but readily soluble in water in the presence of oxygen. The fission reactions operated intermittently for between 10^5 and 10^6 years.

Fig. 9.10. Remains of one of the Oklo reactors. © CEA

The natural fission reactors at Oklo can be considered as analogues for very old radioactive waste repositories and can be used to study the transport behaviour of transuranic nuclides and stability of uranium minerals which have undergone criticality.

Nuclear Tests in the South Pacific

France began atmospheric nuclear testing in the South Pacific at the atolls of Mururoa and Fangataufa atolls in 1966 [22]. These French Polynesian atolls, were chosen because of their relative isolation and geological characteristics as shown in Fig. 9.11.

The first tests conducted at the Mururoa and Fangataufa sites were atmospheric. Underground testing started in June 1975. In total 41 atmospheric and 134 borehole tests were conducted between 1960 and 1991. A final series of eight tests were conducted between September 1995 and May 1996 after which France signed the Comprehensive Nuclear Test Ban Treaty (CTBT) [23].

Geological and radiological surveillance of the Mururoa and Fangataufa atolls will continue on a periodic basis for many years. Radioactivitiy measurements in air and water will be made together with measurements in soil and sediment and in plants, fish, plankton, shellfish under the auspices of the IAEA.

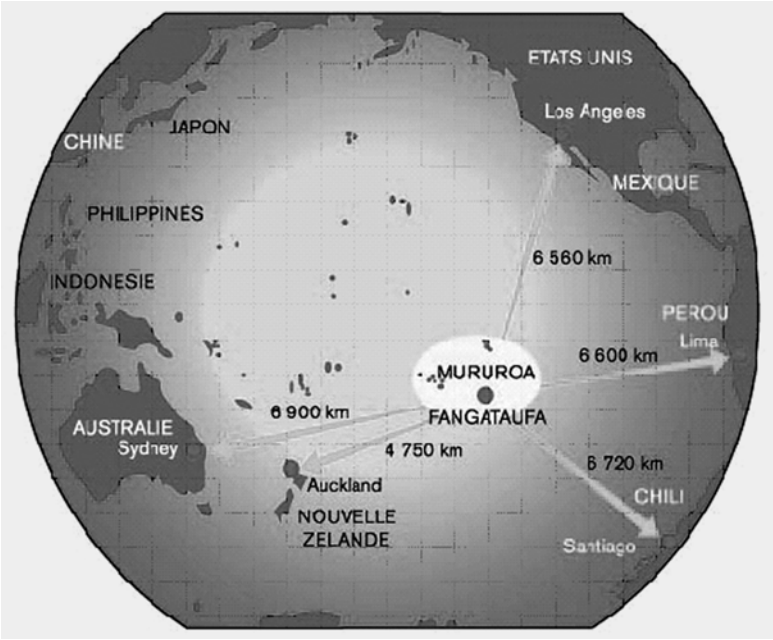


Fig. 9.11. French map showing the location of the Mururoa and Fangataufa atolls [22]

Atoll Geology

Atoll are ring-shaped coral reefs a few metres in height enclosing a lagoon (Fig. 9.12). They are the result of volcanic eruptions that occurred millions of years ago. Fuelled by a hotspot in the Earth's crust, these volcanoes grew some four kilometres in height from the sea floor until they reached the ocean surface where they were capped with several hundreds of metres of carbonate rock from coral accretions. During glaciation periods, the sea level dropped some hundred metres below the top rim of the extinct volcano.

Fig. 9.12. Pacific atoll of Mururoa

Underground Nuclear Explosions

The nuclear tests were carried out at depths of between 500 and 1100 m in the volcanic rock. An underground nuclear explosion generates, apart from radioactivity, intense heat and a shock wave [24]. The rock in the vicinity is melted and vaporized forming a roughly spherical cavity and a pool of molten rock. On cooling, the molten mass in the cavity forms a glass-like lava that contains most of the radioactivity.

The confinement of the radioactivity in the solidified rocks is efficient. The water in the cavities formed contains some thousandths of the total $\beta\gamma$-activity and less than one millionth of the total α-activity. Basaltic glasses have existed for millions of years and show very good stability against the phenomena of natural leaching. Leaching rates of the order of 1 μm per 1000 years have been observed. Leaching rates of similar order of magnitude have been observed in laboratory studies of vitrified nuclear waste.

Radionuclide Inventory

The inventory of long-lived radionuclides resulting from the underground nuclear explosions is shown in Table 9.9. The activities have been estimated from the yields

Table 9.9. Inventory of selected long-lived radionuclides at Mururoa and Fangataufa atolls [25, 26]

	Study data (TBq)		
Radionuclide	Mururoa	Fangataufa	Total
Tritium	232 000	48 000	280 000
Carbon-14	25	2.6	28
Chlorine-36	1.3	0.4	1.7
Calcium-41	1.0	0.3	1.3
Nickel-59	2.9	0.9	3.8
Nickel-63	340	110	450
Selenium-79	0.008	0.003	0.011
Krypton-85	670	380	1 000
Strontium-90	7 300	3 500	10 800
Zirconium-93	0.23	0.09	0.32
Technetium-99	1.9	0.6	2.5
Palladium-107	0.18	0.03	0.21
Iodine-129	0.0047	0.0014	0.0061
Caesium-135	0.20	0.07	0.27
Caesium-137	10 700	4 100	14 800
Neptunium-237	0.22	0.03	0.25
Plutonium-238	185	15	200
Plutonium-239	1 030	70	1 100
Plutonium-240	280	20	300
Plutonium-241	6 200	620	6 800
Americium-241	350	30	380

of the explosions together with reasonable assumptions regarding the proportion of energy from ^{239}Pu, ^{235}U, ^{238}U fission and from fusion of hydrogen isotopes [25].

Following the nuclear tests in the south Pacific atolls of Mururoa and Fangataufa, detailed measurements revealed that the predominant nuclides in marine and terrestrial environments were caesium-137, plutonium-239, and plutonium-240. It was established that the concentrations of radionuclides in coconuts, fish, and shellfish did not exceed a few becquerels per kilogram. Although modelling of the total inventory of radionuclides retained underground indicated that releases will peak in approximately 2500 years, it was concluded that no adverse radiological health effects will arise as a result of the addition of radioactivity to the environment.

The Chernobyl Accident

The Chernobyl power plant is about 7 km from the border with Belarus, with Kiev, the capital of Ukraine, about 100 km to the south with a population of 3.1 million. In the night of 25 April 1986, the explosion of the reactor released one hundred times more

Table 9.10. Current estimate of radionuclide releases during the Chernobyl accident [27, 28]

	Core inventory on 26 April 1986		**Total release during the accident**	
Nuclide	Half-life	Activity (PBq)*	Percent inventory	Activity (PBq)*
^{33}Xe	5.3 d	6 500	100	6 500
^{131}I	8.0 d	3 200	50–60	~1 760
^{134}Cs	2.0 y	180	20–40	~54
^{137}Cs	30.0 y	280	20–40	~85
^{132}Te	78.0 h	2 700	25–60	~1150
^{89}Sr	52.0 d	2 300	4–6	~115
^{90}Sr	28.0 y	200	4–6	~10
^{140}Ba	12.8 d	4 800	4–6	~240
^{95}Zr	65.0 d	5 600	3.5	196
^{99}Mo	67.0 h	4 800	>3.5	>168
^{103}Ru	39.6 h	4 800	>3.5	>168
^{106}Ru	1.0 y	2 100	>3.5	>73
^{141}Ce	33.0 d	5 600	3.5	196
^{144}Ce	285.0 d	3 300	3.5	~196
^{239}Np	2.4 d	27 000	3.5	~95
^{238}Pu	86.0 y	1	3.5	0.035
^{239}Pu	24 400.0 y	0.85	3.5	0.03
^{240}Pu	6 580.0 y	1.2	3.5	0.042
^{241}Pu	13.2 y	170	3.5	~6
^{2421}Cm	163.0 d	26	3.5	~0.9

* 1 PBq = 10^{15} Bq.

radiation than the atom bombs dropped over Hiroshima and Nagasaki. In addition to the reactor's immediate surroundings – an area with a radius of about 30 km – other regions were contaminated, particularly in Belarus, Russia and Ukraine.

The radionuclide releases from the damaged reactor occurred mainly over a 10-day period [27, 28]. From the radiological point of view, ^{131}I and ^{137}Cs were responsible for most of the radiation exposure received by the general population. The releases of ^{131}I and ^{137}Cs are estimated to have been 1760 and 85 PBq, respectively (1 PBq = 10^{15} Bq). The three main areas of contamination, defined as those with ^{137}Cs deposition density greater than 37 kBq/m^2 were in Belarus, the Russian Federation and Ukraine. In northern and eastern Europe, there were many areas with a ^{137}Cs deposition density in the range 37–200 kBq/m^2.

The Chernobyl accident is to date the only nuclear accident to be assigned a 7 on the INES (international nuclear event scale). This rating implies significant health consequences in addition to psychological effect. Of the 600 workers present during the accident, 134 received high doses in the range 0.7–13 Gy and suffered radiation illness. In the few months following the accident, 30 of the high dose victims died. Following the accident, around 200,000 recovery operations workers received doses between 0.01 and 0.5 Gy. Since 1986, the population in the neighbouring territories have been subjected to external and internal exposure from deposited radionuclides.

The Goiânia Radiation Incident – a Benchmark for Radiological Dispersion Devices (RDDs)

The Goiânia Radiation Incident is the most serious event recorded to date involving a medical radiation source [29–31]. Goiânia is the capital of the Brazilian state of Goiás in south-central Brazil with a population of 700,000 (1980). In September 1987, approximately one year after the Chernobyl accident, a radiation source contained in a metal canister was stolen from a radiotherapy machine in an abandoned cancer clinic and sold to a scrap dealer. Some five days later, the dealer opened the metal canister to find a fluorescent powder which was radioactive cesium (^{137}Cs) chloride. The source had a strength of 50 TBq (approx. 1400 Ci). The blue glow from the powder, caused by the absorption of the gamma rays by chlorine and emission of visible light, made it appear valuable. In the following days, the powder was also circulated among family and friends. A six-year-old girl rubbed the powder onto her body and ate a sandwich contaminated with the powder from her hands. In total 244 persons were exposed, and four died. Approximately 100,000 people were screened for contamination. The incident in Goiânia was the second largest radiological accident after Chernobyl and is regarded as a benchmark when discussing the potential consequences of radiological dispersion devices (RDD or "dirty bombs"). The socio-economic impact was such that tourism suffered greatly and it took five years for the gross domestic product to return to pre-1987 levels.

In order to illustrate the potential consequences of such radiological incidents, two idealised cases, involving a) external radiation exposure and b) internal exposure through inhalation, are considered in detail.

External Exposure Due to Radiation from a ^{60}Co Source

Consider a source of ^{60}Co located somewhere in the centre of a city. Since the radioactivity is not dispersed, population exposure occurs only through external radiation. As a source of ^{60}Co, we consider a capsule (used in radiotherapy) containing 1.7 g corresponding to an activity of 7.4×10^{13} Bq (2000 Ci). The gamma dose rate at various distances from the source is shown in Fig. 9.13 neglecting attenuation by buildings (calculated with the Γ-Dose module in Nuclides.net [32]). Results for three calculations are given: in "vacuum" (no absorption by air, no scattering), in air (absorption, no scattering), and in air (absorption and scattering). At 1 m from source the Γ-dose rate is 24.9 Sv h^{-1}. At a distance of approximately 200 m from the source, the dose rate has the value of 0.5 mSv h^{-1}. For an exposure time of 2 h (considered below) the dose received is 1 mSv, the limit for members of the public.

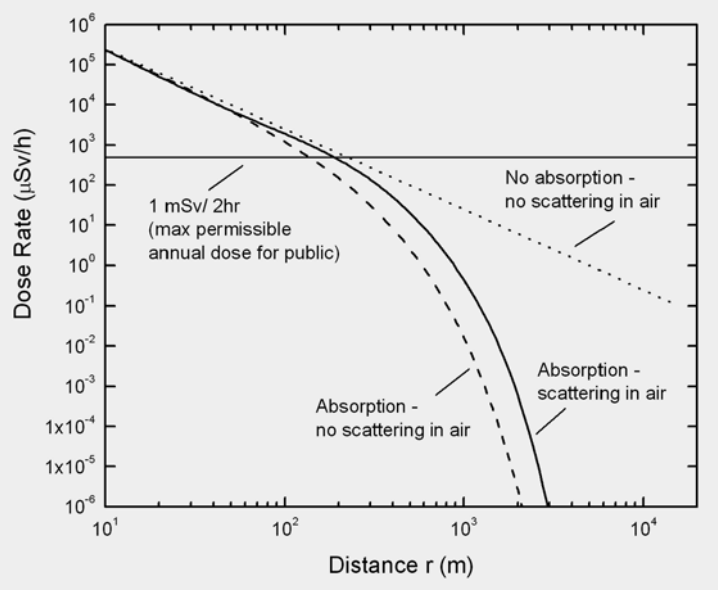


Fig. 9.13. Long-range radiological effects of a ^{60}Co source (7.4×10^{13} Bq). Beyond 100 m, the effects of air attenuation and scattering become important

Such a concealed radioactive source in an open area of high population density could lead to a significant radiation exposure. On the assumption that radiation effects are directly proportional to the radiation dose without threshold, then the sum of all doses to all exposed individuals is the collective effective dose, *CD*. This can be calculated as follows.

The dose rate $\mathrm{d}H(r)/\mathrm{d}t$ is received by the total number of people in a small ring of thickness $\mathrm{d}r$ at distance r. The number of people is this ring is then $\mathrm{d}N = 2\pi r \cdot \mathrm{d}r \cdot \rho_\mathrm{p}$ where ρ_p is the population density (inhabitants per square kilometre). The collective dose is then obtained by integrating this over the area of interest i.e.

$$CD = \sum_i \frac{\mathrm{d}H(r_i)}{\mathrm{d}t} \cdot \mathrm{d}N_i \cdot \Delta t = \sum_i \frac{\mathrm{d}H(r_i)}{\mathrm{d}t} \cdot 2\pi r_i \Delta r_i \rho_\mathrm{p} \Delta t$$

where Δt is the exposure time. For the above source (2000 Ci of ^{60}Co): $A = 7.4 \times 10^{13}$ Bq, an exposure time of 2 hours, a population density of 2600 inh/km^2, $R = 200$ m. Neglecting air attenuation and multiple scattering implies that the dose rate has the form $\mathrm{d}H(r)/\mathrm{d}t = kA/r^2$, where k is the specific gamma dose rate constant. This gives an upper limit to the dose rate as shown in Fig. 9.13 and allows one to obtain a simple expression for the collective dose, i.e.

$$CD = \int_{r_0}^{R} \left(\frac{kA}{r^2}\right) 2\pi r \mathrm{d}r \rho_\mathrm{p} \Delta t = 2\pi k A \rho_\mathrm{p} \Delta t \ln\left(\frac{R}{r_0}\right) ,$$

where the lower limit r_0 has been used to avoid the divergence at $r = 0$. The upper limit for integration R is where the equivalent dose rate reaches the limit for members of the public. Inserting the values $k = 3.37 \times 10^{-7}$ μSv m^2/h Bq [32] leads to the collective dose $CD = 5.3$ manSv. This is within a factor 2 of the more accurate value obtained by numerical integration.

The relationship between the radiation dose and the likelihood of incurring a stochastic effect can be expressed as a risk factor i.e. the likelihood of incurring a stochastic effect = collective dose (Sv)×Risk Factor (Sv^{-1}). The total number of excess cancers is the risk factor multiplied by the collective dose i.e.

$$\text{Total number of cancers} = 0.05\,\mathrm{Sv}^{-1} \times 5.3\,\text{manSv} = 0.27\,\text{persons}\,.$$

Internal Exposure Due to Inhalation of ^{60}Co Dispersed in a Radioactive Cloud

In this scenario, it is assumed that following the detonation of an RDD, radioactive material is dispersed into the atomosphere. To understand the dispersion of this radioactivity under given wind conditions, a simple dispersion model has been developed. It is assumed that as a result of the detonation, the activity S_T has been dispersed uniformly in fine (~ 1 μm) aerosol form resulting in a cylindrical radioactive cloud of radius $r(t)$ and height h. The cloud radius is given by $r(t) = vt$ where v is the horizontal dispersion velocity. This assumption of a cloud consisting of finely dispersed particle aerosol can be considered as a worst case. In reality, following an explosion, only a small percentage of the airborne activity would be in a form of fine (1 μm) aerosol. The dose by inhalation depends on the particle size distribution, and the larger the particle size the lower the dose (particles with aerodynamic diameter of more than 10 μm cannot reach the lungs). In a real case the fraction of radionuclides which is deposited into the lungs is likely below 10% (AMAD 5 μm = 5.8% deposit in the lung; AMAD 1 μm = 11% deposit in the lung).

The cloud location is a function of time and is given by the wind speed w, and the dispersion velocity v as shown in Fig. 9.14. The cloud height is the plume height resulting from detonation. The volume activity $A_\mathrm{V}(t)$ in the cloud is $A_\mathrm{V}(t) = S_\mathrm{T}/(\pi r^2 h) = S_\mathrm{T}/(\pi h v^2 t^2)$. It is assumed that the dose arises from internal exposure due to inhalation (this is usually many orders of magnitude higher than exposure due to external radiation).

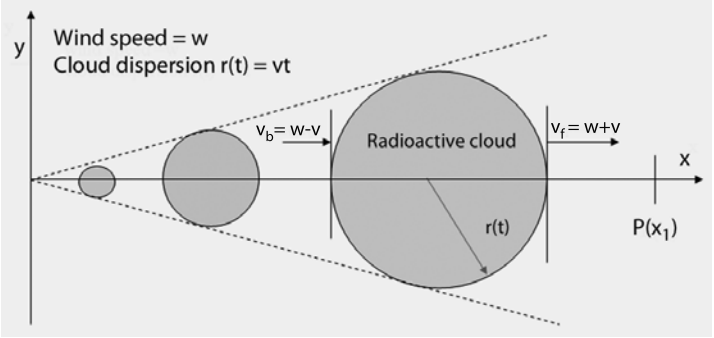


Fig. 9.14. Simplified cloud dispersion model. The cloud is moving with wind speed w (along the x-axis). Dispersion occurs radially such that the cloud radius r at any time t is given by $r(t) = vt$. It is assumed that the aerosol concentration is uniform within the cloud

At any time t, the contribution to the committed effective dose $\mathrm{d}E$ (dose generated by inhaled radioactive material within the next 50 years) received by a person in the cloud due to inhalation in time $\mathrm{d}t$ is given by

$$\mathrm{d}E(t) \equiv e_{\mathrm{inh}} \cdot \mathrm{d}A(t) = e_{\mathrm{inh}} A_V(t) R_{\mathrm{inh}} \mathrm{d}t = e_{\mathrm{inh}} (S_{\mathrm{T}}/\pi h v^2) R_{\mathrm{inh}} (1/t^2) \mathrm{d}t \quad (9.1)$$

where $\mathrm{d}A$ is the total activity intake, and e_{inh} the effective dose coefficient for inhalation. The total activity intake in time $\mathrm{d}t$ is $A_{\mathrm{V}} R_{\mathrm{inh}} \mathrm{d}t$ where A_{V} is the activity per unit volume and $\mathrm{R_{inh}}$ is the inhalation rate ($R_{\mathrm{inh}} = 1.2\,\mathrm{m^3/h}$). Integration leads to the total dose received by a person at x due to the passing cloud, i.e.

$$E(x) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \int_{t_1}^{t_2} \frac{1}{t^2} \mathrm{d}t = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \left(\frac{1}{t_1} - \frac{1}{t_2} \right), \quad (9.2)$$

where t_1 and t_2 are the times at which the cloud front and back surfaces cross the point x. The cloud front surface has a speed of $w + v$ such that $t_1 = x/(w + v)$. For $w > v$, the cloud back surface moves along the x-axis such that $t_2 = x/(w - v)$. For $w \leq v$ (very low wind speeds), the cloud back surface is either stationary or moves along the negative x-axis such that $t_2 = \infty$. Hence:

for $t > x/(w + v)$ and $w > v$:

$$E(x,t) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \frac{(w+v)}{x} \left[1 - \frac{x}{(w+v) \min\left(t, \frac{x}{w-v}\right)} \right], \quad (9.3)$$

for $t > x/(w + v)$ and $w = v$:

$$E(x,t) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \frac{(w+v)}{x} \left[1 - \frac{x}{(w+v)t} \right]. \quad (9.4)$$

The expressions for the committed effective dose given in equations (9.3–9.4) are applied to the dispersion of ^{60}Co. The result are shown in Fig. 9.15 for a wind

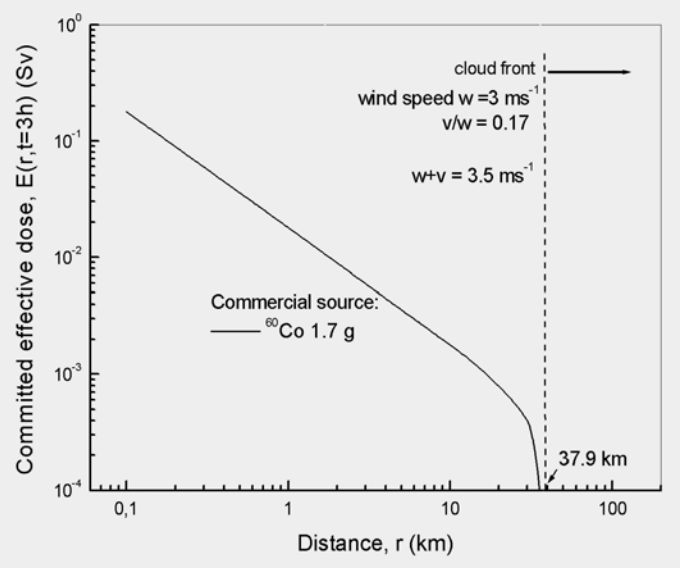


Fig. 9.15. Committed effective dose as a function of distance x from the detonation point in a moving radioactive cloud (wind speed $w = 3\,\mathrm{m\,s^{-1}}$, dispersion speed $v = 0.5\,\mathrm{m\,s^{-1}}$). It is assumed that the fine aerosol is dispersed uniformly in a cylindrical cloud with radius $r(t)$ and height h (see Fig. 9.14).

speed of $3\,\mathrm{m\,s^{-1}}$ and a radial dispersion speed of $0.5\,\mathrm{m\,s^{-1}}$. The simple analytical model can reproduce the more sophisticated code results very well.

A number of studies have already addressed the problem of RDDs fabricated from isotopes destined for medical and industrial purposes [33–40], such as ^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, etc. The amount of radioactive material contained in such sources varies considerably but can be as high as tens of thousands of curies. These studies conclude that the consequences of an RDD using such radioactive materials are much less severe than those of a nuclear explosion. Compared to fission or fusion devices, the amount of radioactivity disperse is much less as is the energy released from detonation. The main consequence is social and economic disruption with limited casualties [41] and that expensive and time consuming decontamination will be required.