9
Radiological aspects

The objective of this chapter is to provide criteria with which to assess the safety of drinking-water with respect to its radionuclide content. The Guidelines do not differentiate between naturally occurring and artificial or human-made radionuclides.

The guidance values for radioactivity in drinking-water recommended in the first edition of the Guidelines were based on the risks of exposure to radiation sources and the health consequences of exposure to radiation. The second edition of the Guidelines incorporated the 1990 recommendations of the International Commission on Radiological Protection (ICRP, 1991). The third edition incorporates recent developments, including the ICRP publications on prolonged exposures and on dose coefficients.

Radiological hazards may derive from ionizing radiation emitted by a number of radioactive substances (chemicals) in drinking-water. Such hazards from drinking-water are rarely of public health significance, and radiation exposure from drinking-water must be assessed alongside exposure from other sources.

The approach taken in the Guidelines for controlling radiological hazards has two stages:

— initial screening for gross alpha and/or beta activity to determine whether the activity concentrations (in Bq/litre) are below levels at which no further action is required; and
— if these screening levels are exceeded, investigation of the concentrations of individual radionuclides and comparison with specific guidance levels.

The risk due to radon in drinking-water derived from groundwater is typically low compared with that due to total inhaled radon but is distinct, as exposure occurs through both consumption of dissolved gas and inhalation of released radon and its daughter radionuclides. Greatest exposure is general ambient inhalation and inhalation from terrestrial sources, where the gas is infiltrating into dwellings, especially into basements. Radon of groundwater origin would usually be a small increment of the total, but may indicate deposits in the region that are emitting into basements.

The screening and guidance levels apply to routine ("normal") operational conditions of existing or new drinking-water supplies. They do not apply to a water supply

contaminated during an emergency involving the release of radionuclides into the environment. Guidance and generic action levels covering emergency situations are available elsewhere (IAEA, 1996, 1997, 1999, 2002).

The current Guidelines are based on:

— a recommended reference dose level (RDL) of the committed effective dose, equal to 0.1 mSv from 1 year's consumption of drinking-water (from the possible total radioactive contamination of the annual drinking-water consumption). This comprises 10% of the intervention exemption level recommended by the ICRP for dominant commodities (e.g., food and drinking-water) for prolonged exposure situations, which is most relevant to long-term consumption of drinking-water by the public (ICRP, 2000). The RDL of 0.1 mSv is also equal to 10% of the dose limit for members of the population, recommended by both the ICRP (1991) and the International Basic Safety Standards (IAEA, 1996). These are accepted by most WHO Member States, the European Commission, FAO and WHO.
— dose coefficients for adults, provided by the ICRP.

The additional risk to health from exposure to an annual dose of 0.1 mSv associated with the intake of radionuclides from drinking-water is considered to be low for the following reasons:

- The nominal probability coefficient for radiation-induced stochastic health effects, which include fatal cancer, non-fatal cancer and severe hereditary effects for the whole population, is 7.3×10^{-2}/Sv (ICRP, 1991). Multiplying this by an RDL equal to 0.1 mSv annual exposure via drinking-water gives an estimated upper-bound lifetime risk of stochastic health effects of approximately 10^{-4}, which can be considered small in comparison with many other health risks. This reference risk estimation for radionuclides is quite reliable due to the extensive scientific databases that have included human population exposure data. As with chemical carcinogen risk extrapolations, the lower-bound risk is zero.
- Background radiation exposures vary widely across the Earth, but the average is about 2.4 mSv/year, with the highest local levels being up to 10 times higher without any detected increased health risks from population studies; 0.1 mSv therefore represents a small addition to background levels.

9.1 Sources and health effects of radiation exposure

Environmental radiation originates from a number of naturally occurring and human-made sources. Radioactive materials occur naturally everywhere in the environment (e.g., uranium, thorium and potassium-40). By far the largest proportion of human exposure to radiation comes from natural sources – from external sources of radiation, including cosmic and terrestrial radiation, and from inhalation or ingestion of radioactive materials (Figure 9.1). The United Nations Scientific Committee

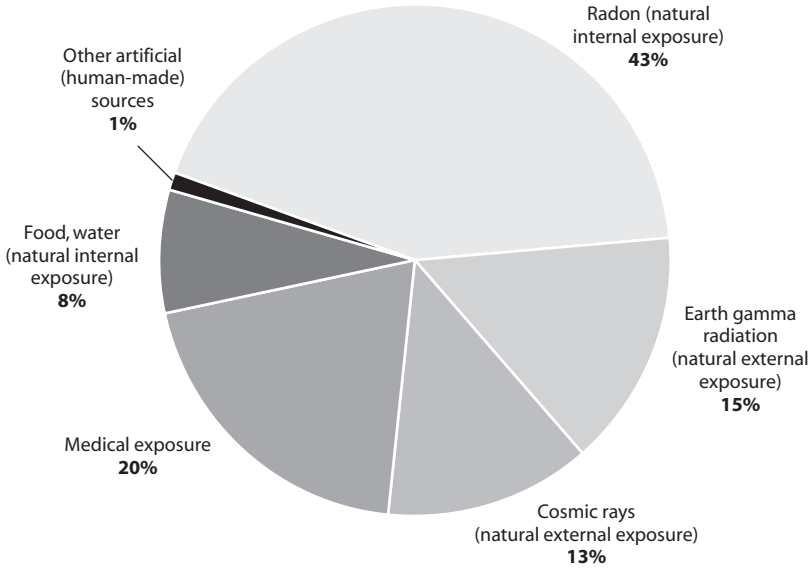

Figure 9.1 Sources and distribution of average radiation exposure for the world population

on the Effects of Atomic Radiation (UNSCEAR, 2000) has estimated that the global average annual human exposure from natural sources is 2.4 mSv/year (Table 9.1). Some sources (e.g., uranium) can be concentrated during extraction by mining and other industrial activities.

There are large local variations in human exposure to radiation, depending on a number of factors, such as height above sea level, the amount and type of radionuclides in the soil (terrestrial exposure), the composition of radionuclides in the air, food and drinking-water and the amount taken into the body via inhalation or ingestion. There are certain areas of the world, such as parts of the Kerala state in India and the Pocos del Caldas plateau in Brazil, where levels of background radiation are

Table 9.1 Average radiation dose from natural sources

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External exposure		
Cosmic rays	0.4	0.3–1.0
Terrestrial gamma rays[a]	0.5	0.3–0.6
Internal exposure		
Inhalation (mainly radon)	1.2	0.2–10[b]
Ingestion (food and drinking-water)	0.3	0.2–0.8
Total	**2.4**	**1–10**

[a] Terrestrial exposure is due to radionuclides in the soil and building materials.
[b] Dose from inhalation of radon may exceed 10 mSv/year in certain residential areas.
Source: UNSCEAR (2000).

relatively high. Levels of exposure for the general population in such areas may be up to 10 times higher than the average background level of 2.4 mSv given in Table 9.1. No deleterious health effects associated with this elevated radiation exposure have been detected (UNSCEAR, 2000).

Several radioactive compounds may be released into the environment, and hence into drinking-water supplies, from human activities and human-made sources (e.g., from medical or industrial use of radioactive sources). The worldwide per capita effective dose from diagnostic medical examination in 2000 was 0.4 mSv/year (typical range is 0.04–1.0 mSv/year, depending on level of health care). There is only a very small worldwide contribution from nuclear power production and nuclear weapons testing. The worldwide annual per capita effective dose from nuclear weapons testing in 2000 was estimated at 0.005 mSv; from the Chernobyl accident, 0.002 mSv; and from nuclear power production, 0.0002 mSv (UNSCEAR, 2000).

9.1.1 Radiation exposure through drinking-water

Radioactive constituents of drinking-water can result from:

- naturally occurring radioactive species (e.g., radionuclides of the thorium and uranium decay series in drinking-water sources), in particular radium-226/228 and a few others;
- technological processes involving naturally occurring radioactive materials (e.g., the mining and processing of mineral sands or phosphate fertilizer production);
- radionuclides discharged from nuclear fuel cycle facilities;
- manufactured radionuclides (produced and used in unsealed form), which might enter drinking-water supplies as a result of regular discharges and, in particular, in case of improper medical or industrial use and disposal of radioactive materials; such incidents are different from emergencies, which are outside the scope of these Guidelines; and
- past releases of radionuclides into the environment, including water sources.

The contribution of drinking-water to total exposure is typically very small and is due largely to naturally occurring radionuclides in the uranium and thorium decay series. Radionuclides from the nuclear fuel cycle and from medical and other uses of radioactive materials may, however, enter drinking-water supplies. The contributions from these sources are normally limited by regulatory control of the source or practice, and it is normally through this regulatory mechanism that remedial action should be taken in the event that such sources cause concern by contaminating drinking-water.

9.1.2 Radiation-induced health effects through drinking-water

There is evidence from both human and animal studies that radiation exposure at low to moderate doses may increase the long-term incidence of cancer. Animal studies in particular suggest that the rate of genetic malformations may be increased by radiation exposure.

No deleterious radiological health effects are expected from consumption of drinking-water if the concentrations of radionuclides are below the guidance levels (equivalent to a committed effective dose below 0.1 mSv/year).

Acute health effects of radiation, leading to reduced blood cell counts and, in very severe cases, death, occur at very high doses of exposure of the whole body or large part of the body (IAEA, 1998). Due to the low levels of radionuclides typically found in drinking-water supplies, acute health effects of radiation are not a concern for drinking-water supplies.

9.2 Units of radioactivity and radiation dose

The SI unit of radioactivity is the becquerel (Bq), where 1 Bq = 1 disintegration per second. Guidance levels for drinking-water are given as the activity of the radionuclide per litre, called the activity concentration (Bq/litre). The radiation dose resulting from ingestion of a radionuclide depends on a number of chemical and biological factors. These include the fraction of the intake that is absorbed from the gut, the organs or tissues to which the radionuclide is transported and the time during which the radionuclide remains in the organ or tissue before excretion. The nature of the radiation emitted on decay and the sensitivity of the irradiated organs or tissues to radiation must also be considered.

The absorbed dose refers to how much energy is deposited in material by the radiation. The SI unit for absorbed dose is the gray (Gy), where 1 Gy = 1 J/kg (joule per kilogram).

The equivalent dose is the product of the absorbed dose and a factor related to the particular type of radiation (depending on the ionizing capacity and density).

The effective dose of radiation received by a person is, in simple terms, the sum of the equivalent doses received by all tissues or organs, weighted for "tissue weighting factors." These reflect different sensitivities to radiation of different organs and tissues in the human body. The SI unit for the equivalent and effective dose is the sievert (Sv), where 1 Sv = 1 J/kg.

To reflect the persistence of radionuclides in the body once ingested, the committed effective dose is a measure of the total effective dose received over a lifetime (70 years) following intake of a radionuclide (internal exposure).

The term "dose" may be used as a general term to mean either absorbed dose (Gy) or effective dose (Sv), depending on the situation. For monitoring purposes, doses are determined from the activity concentration of the radionuclide in a given material. In the case of water, activity concentration is given in becquerels per litre (Bq/litre). This value can be related to an effective dose per year (mSv/year) using a dose coefficient (mSv/Bq) and the average annual consumption of water (litres/year).

The effective dose arising from the ingestion of a radioisotope in a particular chemical form can be estimated using a dose coefficient. Data for age-related dose coefficients for ingestion of radionuclides have been published by the ICRP and the International Atomic Energy Agency (IAEA). Table 9.2 shows the dose coefficients for

Table 9.2 Dose coefficients for ingestion of radionuclides by adult members of the public

Category	Radionuclide	Dose coefficient (mSv/Bq)
Natural uranium series	Uranium-238	4.5×10^{-5}
	Uranium-234	4.9×10^{-5}
	Thorium-230	2.1×10^{-4}
	Radium-226	2.8×10^{-4}
	Lead-210	6.9×10^{-4}
	Polonium-210	1.2×10^{-3}
Natural thorium series	Thorium-232	2.3×10^{-4}
	Radium-228	6.9×10^{-4}
	Thorium-228	7.2×10^{-5}
Fission products	Caesium-134	1.9×10^{-5}
	Caesium-137	1.3×10^{-5}
	Strontium-90	2.8×10^{-5}
	Iodine-131	2.2×10^{-5}
Other radionuclides	Tritium	1.8×10^{-8}
	Carbon-14	5.8×10^{-7}
	Plutonium-239	2.5×10^{-4}
	Americium-241	2.0×10^{-4}

naturally occurring radionuclides or those arising from human activities that might be found in drinking-water supplies (IAEA, 1996; ICRP, 1996).

9.3 Guidance levels for radionuclides in drinking-water

The guidance levels for radionuclides in drinking-water are presented in Table 9.3 for radionuclides originating from natural sources or discharged into the environment as the result of current or past activities. These levels also apply to radionuclides released due to nuclear accidents that occurred more than 1 year previously. The activity concentration values in Table 9.3 correspond to an RDL of 0.1 mSv/year from each radionuclide listed if their concentration in the drinking-water consumed during the year does not exceed these values. The associated risk estimate was given at the beginning of this chapter. However, for the first year immediately after an accident, generic action levels for foodstuffs apply as described in the International Basic Safety Standards (IAEA, 1996) and other relevant WHO and IAEA publications (WHO, 1988; IAEA, 1997, 1999).

The guidance levels for radionuclides in drinking-water were calculated by the following equation:

$$GL = IDC/(h_{ing} \cdot q)$$

where:

GL = guidance level of radionuclide in drinking-water (Bq/litre),
IDC = individual dose criterion, equal to 0.1 mSv/year for this calculation,
h_{ing} = dose coefficient for ingestion by adults (mSv/Bq),
q = annual ingested volume of drinking-water, assumed to be 730 litres/year.

Table 9.3 Guidance levels for radionuclides in drinking-water

Radionuclides	Guidance level (Bq/litre)[a]	Radionuclides	Guidance level (Bq/litre)[a]	Radionuclides	Guidance level (Bq/litre)[a]
^{3}H	10 000	^{97m}Tc	100	^{149}Pm	100
^{7}Be	10 000	^{99}Tc	100	^{151}Sm	1000
^{14}C	100	^{97}Ru	1000	^{153}Sm	100
^{22}Na	100	^{103}Ru	100	^{152}Eu	100
^{32}P	100	^{106}Ru	10	^{154}Eu	100
^{33}P	1 000	^{105}Rh	1000	^{155}Eu	1000
^{35}S	100	^{103}Pd	1000	^{153}Gd	1000
^{36}Cl	100	^{105}Ag	100	^{160}Tb	100
^{45}Ca	100	^{110m}Ag	100	^{169}Er	1000
^{47}Ca	100	^{111}Ag	100	^{171}Tm	1000
^{46}Sc	100	^{109}Cd	100	^{175}Yb	1000
^{47}Sc	100	^{115}Cd	100	^{182}Ta	100
^{48}Sc	100	^{115m}Cd	100	^{181}W	1000
^{48}V	100	^{111}In	1000	^{185}W	1000
^{51}Cr	10 000	^{114m}In	100	^{186}Re	100
^{52}Mn	100	^{113}Sn	100	^{185}Os	100
^{53}Mn	10 000	^{125}Sn	100	^{191}Os	100
^{54}Mn	100	^{122}Sb	100	^{193}Os	100
^{55}Fe	1 000	^{124}Sb	100	^{190}Ir	100
^{59}Fe	100	^{125}Sb	100	^{192}Ir	100
^{56}Co	100	^{123m}Te	100	^{191}Pt	1000
^{57}Co	1 000	^{127}Te	1000	^{193m}Pt	1000
^{58}Co	100	^{127m}Te	100	^{198}Au	100
^{60}Co	100	^{129}Te	1000	^{199}Au	1000
^{59}Ni	1 000	^{129m}Te	100	^{197}Hg	1000
^{63}Ni	1 000	^{131}Te	1000	^{203}Hg	100
^{65}Zn	100	^{131m}Te	100	^{200}Tl	1000
^{71}Ge	10 000	^{132}Te	100	^{201}Tl	1000
^{73}As	1 000	^{125}I	10	^{202}Tl	1000
^{74}As	100	^{126}I	10	^{204}Tl	100
^{76}As	100	^{129}I	1	^{203}Pb	1000
^{77}As	1 000	^{131}I	10	^{210}Pb[b]	0.1
^{75}Se	100	^{129}Cs	1000	^{206}Bi	100
^{82}Br	100	^{131}Cs	1000	^{207}Bi	100
^{86}Rb	100	^{132}Cs	100	^{210}Bi[b]	100
^{85}Sr	100	^{134}Cs	10	^{210}Po[b]	0.1
^{89}Sr	100	^{135}Cs	100	^{223}Ra[b]	1
^{90}Sr	10	^{136}Cs	100	^{224}Ra[b]	1
^{90}Y	100	^{137}Cs	10	^{225}Ra	1
^{91}Y	100	^{131}Ba	1000	^{226}Ra[b]	1
^{93}Zr	100	^{140}Ba	100	^{228}Ra[b]	0.1
^{95}Zr	100	^{140}La	100	^{227}Th[b]	10
^{93m}Nb	1 000	^{139}Ce	1000	^{228}Th[b]	1
^{94}Nb	100	^{141}Ce	100	^{229}Th	0.1
^{95}Nb	100	^{143}Ce	100	^{230}Th[b]	1
^{93}Mo	100	^{144}Ce	10	^{231}Th[b]	1000
^{99}Mo	100	^{143}Pr	100	^{232}Th[b]	1
^{96}Tc	100	^{147}Nd	100	^{234}Th[b]	100
^{97}Tc	1000	^{147}Pm	1000	^{230}Pa	100

continued

Table 9.3 ***Continued***

Radionuclides	Guidance level (Bq/litre)	Radionuclides	Guidance level (Bq/litre)	Radionuclides	Guidance level (Bq/litre)
^{231}Pa[b]	0.1	^{238}Pu	1	^{247}Cm	1
^{233}Pa	100	^{239}Pu	1	^{248}Cm	0.1
^{230}U	1	^{240}Pu	1	^{249}Bk	100
^{231}U	1 000	^{241}Pu	10	^{246}Cf	100
^{232}U	1	^{242}Pu	1	^{248}Cf	10
^{233}U	1	^{244}Pu	1	^{249}Cf	1
^{234}U[b]	1	^{241}Am	1	^{250}Cf	1
^{235}U[b]	1	^{242}Am	1000	^{251}Cf	1
^{236}U[b]	1	^{242m}Am	1	^{252}Cf	1
^{237}U	100	^{243}Am	1	^{253}Cf	100
^{238}U[b,c]	10	^{242}Cm	10	^{254}Cf	1
^{237}Np	1	^{243}Cm	1	^{253}Es	10
^{239}Np	100	^{244}Cm	1	^{254}Es	10
^{236}Pu	1	^{245}Cm	1	^{254m}Es	100
^{237}Pu	1000	^{246}Cm	1		

[a] Guidance levels are rounded according to averaging the log scale values (to 10^n if the calculated value was below 3×10^n and above $3 \times 10^{n-1}$).
[b] Natural radionuclides.
[c] The provisional guideline value for uranium in drinking-water is 15 µg/litre based on its chemical toxicity for the kidney (see section 8.5).

The higher age-dependent dose coefficients calculated for children (accounting for the higher uptake and/or metabolic rates) do not lead to significantly higher doses due to the lower mean volume of drinking-water consumed by infants and children. Consequently, the recommended RDL of committed effective dose of 0.1 mSv/year from 1 year's consumption of drinking-water applies independently of age.

9.4 Monitoring and assessment for dissolved radionuclides

9.4.1 Screening of drinking-water supplies

The process of identifying individual radioactive species and determining their concentration requires sophisticated and expensive analysis, which is normally not justified, because the concentrations of radionuclides in most circumstances are very low. A more practical approach is to use a screening procedure, where the total radioactivity present in the form of alpha and beta radiation is first determined, without regard to the identity of specific radionuclides.

Screening levels for drinking-water below which no further action is required are 0.5 Bq/litre for gross alpha activity and 1 Bq/litre for gross beta activity. The gross beta activity screening level was published in the second edition of the Guidelines and, in the worse case (radium-222), would lead to a dose close to the guidance RDL of 0.1 mSv/year. The screening level for gross alpha activity is 0.5 Bq/litre (instead of the former 0.1 Bq/litre), as this activity concentration reflects values nearer the radionuclide-specific guidance RDL.

9.4.2 Strategy for assessing drinking-water

If either of the screening levels is exceeded, then the specific radionuclides producing this activity should be identified and their individual activity concentrations measured. From these data, an estimate of committed effective dose for each radionuclide should be made and the sum of these doses determined. If the following additive formula is satisfied, no further action is required:

$$\sum_i \frac{C_i}{GL_i} \leq 1$$

where:

C_i = the measured activity concentration of radionuclide i, and
GL_i = the guidance level value (see Table 9.3) of radionuclide i that, at an intake of 2 litres/day for 1 year, will result in a committed effective dose of 0.1 mSv/year.

Where the sum exceeds unity for a single sample, the RDL of 0.1 mSv would be exceeded only if the exposure to the same measured concentrations were to continue for a full year. *Hence, such a sample does not in itself imply that the water is unsuitable for consumption* but should be regarded as an indication that further investigation, including additional sampling, is needed. Gross beta and gross alpha activity screening has to be repeated first, then radionuclide-specific analysis conducted only if subsequently measured gross values exceed the recommended practical screening values (1 Bq/litre and 0.5 Bq/litre, respectively).

The application of these recommendations is summarized in Figure 9.2.

The gross beta measurement includes a contribution from potassium-40, a beta emitter that occurs naturally in a fixed ratio to stable potassium. Potassium is an essential element for humans and is absorbed mainly from ingested food. Potassium-40 does not accumulate in the body but is maintained at a constant level independent of intake. The contribution of potassium-40 to beta activity should therefore be subtracted following a separate determination of total potassium. The specific activity of potassium-40 is 30.7 Bq/g of potassium. However, not all the radiation from potassium-40 appears as beta activity. The beta activity of potassium-40 is 27.6 Bq/g of stable potassium, which is the factor that should be used to calculate the beta activity due to potassium-40.

9.4.3 Remedial measures

If the RDL of 0.1 mSv/year is being exceeded on aggregate, then the options available to the competent authority to reduce the dose should be examined. Where remedial measures are contemplated, any strategy considered should first be justified (in the sense that it achieves a net benefit) and then optimized in accordance with the recommendations of ICRP (1989, 1991) in order to produce the maximum net benefit.

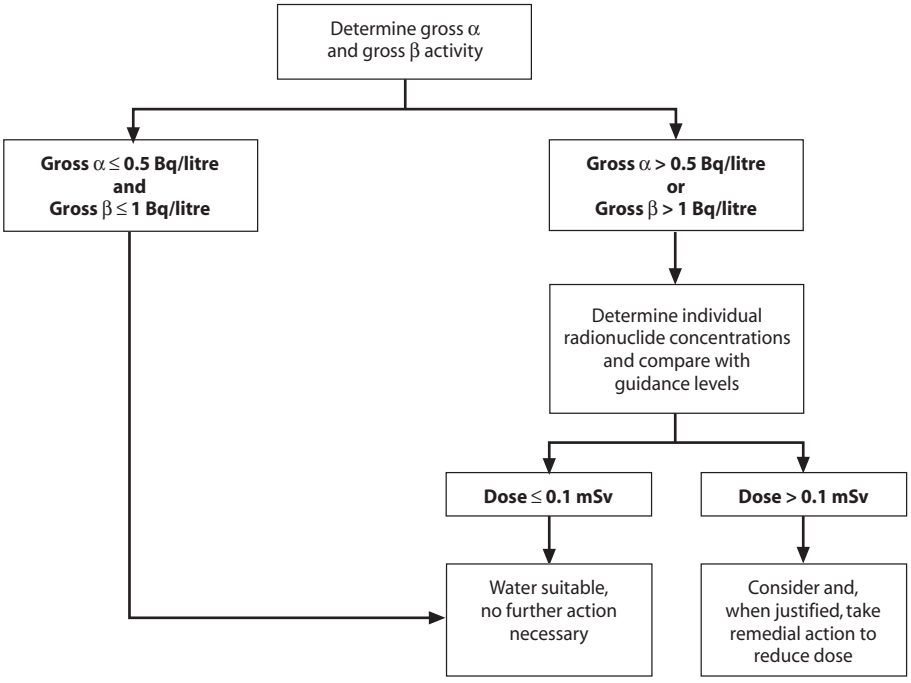

Figure 9.2 Application of screening and guidance levels for radionuclides in drinking-water

9.5 Radon

9.5.1 Radon in air and water

The largest fraction of natural radiation exposure comes from radon, a radioactive gas (see Table 9.1 and Figure 9.1), due to decay of radium contained in rocks and soil as part of the uranium radionuclide chain. The term radon in general refers mostly to radon-222. Radon is present virtually everywhere on Earth, but particularly in the air over land and in buildings.

Underground rock containing natural uranium continuously releases radon into water in contact with it (groundwater). Radon is readily released from surface water; consequently, groundwater has potentially much higher concentrations of radon than surface water. The average concentration of radon is usually less than 0.4 Bq/litre in public water supplies derived from surface waters and about 20 Bq/litre from groundwater sources. However, some wells have been identified with higher concentrations, up to 400 times the average, and in rare cases exceeding 10 kBq/litre.

In assessing the dose from radon ingestion, it is important that water processing technology that can remove radon be considered before consumption is taken into account. Moreover, the use of radon-containing groundwater supplies not treated for radon removal (usually by aeration) for general domestic purposes will increase the levels of radon in the indoor air, thus increasing the dose from indoor inhalation. This

dose depends markedly on the forms of domestic usage and housing construction (NCRP, 1989), because most of the indoor air radon usually enters from the foundation of the house in contact with the ground rather than from the water. The amount

and form of water intake, other domestic usage of water and the construction of houses vary widely throughout the world.

UNSCEAR (2000) refers to a US NAS (1999) report and calculates the "average doses from radon in drinking water to be as low as 0.025 mSv/year via inhalation and 0.002 mSv/year from ingestion" compared with the inhalation dose of 1.1 mSv/year from radon and its decay products in air.

9.5.2 Risk

Large pooled studies of indoor radon and lung cancer risk have recently become available. The European pooled analysis of 13 indoor radon studies estimated a 16% risk increase per 100 Bq/m^3 (Darby et al., 2005). Based on these data, radon accounts for about 9% of all lung cancer deaths and 2% of total cancer deaths in Europe. Similar results were obtained from the joint analysis of North American radon studies (Krewski et al., 2005).

For the USA, the US EPA has estimated that radon causes about 21 000 lung cancer deaths per year (with an uncertainty range of 8000–45 000), out of about 160 000 annual lung cancer deaths (US EPA, 2003). Radon is the second leading cause of lung cancer, after smoking.

US NAS (1999) reports an approximately 100-fold smaller risk from exposure to radon in drinking-water (i.e., 183 deaths each year). In addition to the 19 000 deaths from lung cancer caused by radon in indoor air, a further 160 were estimated to result from inhaling radon that was emitted from water used in the home. For comparison, about 700 lung cancer deaths each year were attributed to exposure to natural levels of radon while people are outdoors.

The US NAS (1999) also assessed that the risk of stomach cancer caused by drinking-water that contains dissolved radon is extremely small, with the probability of about 20 deaths annually compared with the 13 000 deaths from stomach cancer that arise each year from other causes in the USA.

9.5.3 Guidance on radon in drinking-water supplies

Controls should be implemented if the radon concentration of drinking-water for public water supplies exceeds 100 Bq/litre. Any new, especially public, drinking-water supply using groundwater should be tested prior to being used for general consumption. If the radon concentration exceeds 100 Bq/litre, treatment of the water source (see section 9.5.4) should be undertaken to reduce the radon levels to well below 100 Bq/litre. Appropriate treatments include air stripping, aeration systems or – for small water supplies – activated carbon adsorption. If there are significant amounts of radon-producing minerals around the water source, then it may be appropriate for larger drinking-water supplies to test for radon concentration periodically – for example, every 5 years.

9.5.4 Treatment and control methods and technical achievability

Radon, being a gas, is relatively easy to remove by air stripping. Removal efficiencies of >99% were obtained with diffuse bubble and packed tower aeration at air:water ratios of 15:1 and 5:1, respectively (Kinner et al., 1990). Other investigations focusing on aeration at public waterworks have given similar results, with 67–99% efficiencies (Annanmäki & Turtiainen, 2000). This is the preferred method of treatment.

GAC is also effective in removing radon from water, with removals of 70–100% (Lykins et al., 1992). The amount of radon removed by activated carbon is effectively unlimited, because the adsorbed radon decays into other radioactive products, such as ^{210}Pb. As the adsorbed radon decays, radioactive progeny emitting gamma radiation is produced, possibly creating a disposal problem (Castle, 1988). Elevated gamma dose rates (up to 120 μSv/h) near the filter have been recorded (Annanmäki & Turtiainen, 2000). Screening of the GAC filter could be required. In some circumstances, a twin tank system, which introduces a time delay that allows the radon to decay to a significant extent, may be a low-cost option.

9.6 Sampling, analysis and reporting

9.6.1 Measuring gross alpha and gross beta activity concentrations

To analyse drinking-water for gross alpha and gross beta activities (excluding radon), the most common approach is to evaporate a known volume of the sample to dryness and measure the activity of the residue. As alpha radiation is easily absorbed within a thin layer of solid material, the reliability and sensitivity of the method for alpha determination may be reduced in samples with a high TDS content.

Table 9.4 Methods for the analysis of gross alpha and gross beta activities in drinking-water

Method, reference	Technique	Detection limit	Application
International Organization for Standardization: ISO-9695 (for gross beta) ISO-9696 (gross alpha) (ISO, 1991a, 1991b)	Evaporation	0.02–0.1 Bq/litre	Groundwater with TDS greater than 0.1 g/litre
American Public Health Association (APHA, 1998)	Co-precipitation	0.02 Bq/litre	Surface water and groundwater (TDS is not a factor)

Where possible, standardized methods should be used to determine concentrations of gross alpha and gross beta activities. Three procedures for this analysis are listed in Table 9.4.

The determination of gross beta activity using the evaporation method includes the contribution from potassium-40. An additional analysis of total potassium is therefore required if the gross beta screening value is exceeded.

The co-precipitation technique (APHA, 1998) excludes the contribution due to potassium-40; therefore, determination of total potassium is not necessary. This method is not applicable to assessment of water samples containing certain fission products, such as caesium-137. However, under normal circumstances, concentrations of fission products in drinking-water supplies are extremely low.

9.6.3 Measuring radon

There are difficulties in deriving activity concentrations of radon-222 in drinking-water arising from the ease with which radon is released from water during handling. Stirring and transferring water from one container to another will liberate dissolved radon. According to the widely used Pylon technique (Pylon, 1989, 2003), detection of radon in drinking-water is performed using a water degassing unit and Lucas scintillation chambers. Water that has been left to stand will have reduced radon activity, and boiling will remove radon completely.

9.6.4 Sampling

New groundwater sources for public supplies should be sampled at least once to determine their suitability for drinking-water supply before design and construction to characterize the radiological quality of the water supply and to assess any seasonal variation in radionuclide concentrations. This should include analysis for radon and radon daughters.

Once measurements indicate the normal range of the supply, then the sampling frequency can be reduced to, for example, every 5 years. However, if sources of potential radionuclide contamination exist nearby (e.g., mining activity or nuclear reactors), then sampling should be more frequent. Less significant surface and underground drinking-water sources may be sampled less frequently.

Levels of radon and radon daughters in groundwater supplies are usually stable over time. Monitoring of water for radon and its daughters can therefore be relatively infrequent. Knowledge of the geology of the area should be considered in determining whether the source is likely to contain significant concentrations of radon and radon daughters. An additional risk factor would be the presence of mining in the vicinity; in such circumstances, more frequent monitoring may be appropriate.

Guidance on assessing water quality, sampling techniques and programmes and the preservation and handling of samples is given in the Australian and New Zealand Standard (AS, 1998).

9.6.5 Reporting of results

The analytical results for each sample should contain the following information:

- sample identifying code or information;
- reference date and time for the reported results (e.g., sample collection date);
- identification of the standard analytical method used or a brief description of any non-standard method used;
- identification of the radionuclide(s) or type and total radioactivity determined;
- measurement-based concentration or activity value calculated using the appropriate blank for each radionuclide;
- estimates of the counting uncertainty and total projected uncertainty; and
- minimum detectable concentration for each radionuclide or parameter analysed.

The estimate of total projected uncertainty of the reported result should include the contributions from all the parameters within the analytical method (i.e., counting and other random and systematic uncertainties or errors).