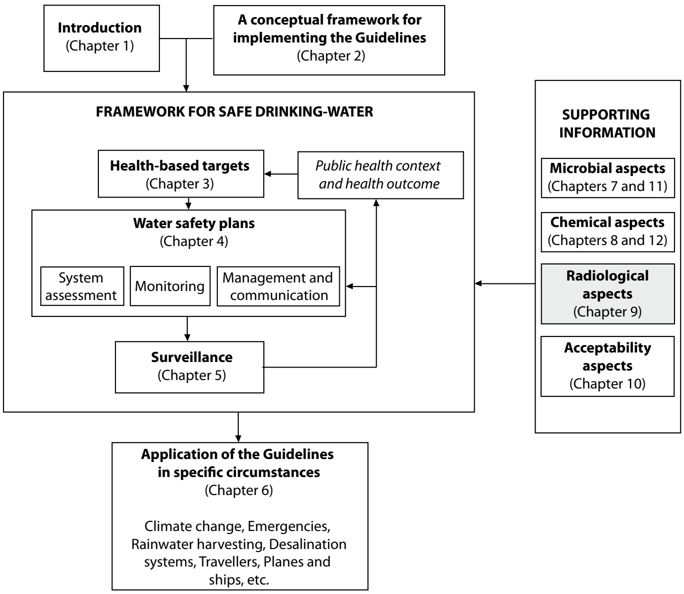
9
Radiological aspects



Drinking-water may contain radioactive substances ("radionuclides") that could present a risk to human health. These risks are normally small compared with the risks from microorganisms and chemicals that may be present in drinking-water. Except in extreme circumstances, the radiation dose resulting from the ingestion of radionuclides in drinking-water is much lower than that received from other sources of radiation. The objective of this chapter is to provide criteria with which to assess the safety of drinking-water with respect to its radionuclide content and to provide guidance on reducing health risks by taking measures to decrease radionuclide concentrations, and therefore radiation doses, in situations where this is considered necessary.

In terms of health risk assessment, the Guidelines do not differentiate between radionuclides that occur naturally and those that arise from human activities. However, in terms of risk management, a differentiation is made because, in principle, human-made radionuclides are often controllable at the point at which they enter the water supply. Naturally occurring radionuclides, in contrast, can potentially enter the water supply at any point, or at several points, prior to consumption. For this reason, naturally occurring radionuclides in drinking-water are often less amenable to control.

Naturally occurring radionuclides in drinking-water usually give radiation doses higher than those provided by artificially produced radionuclides and are therefore of greater concern. Radiological risks are best controlled through a preventive risk management approach following the framework for safe drinking-water (see chapter 2) and the water safety plan approach (see chapter 4). When considering what action to take in assessing and managing radiological risks, care should be taken to ensure that scarce resources are not diverted away from other, more important public health concerns.

The screening levels and guidance levels for radioactivity presented in these Guidelines are based on the latest recommendations of the International Commission on Radiological Protection (ICRP, 2008).

Some drinking-water supplies, in particular those sourced from groundwater, may contain radon, a radioactive gas. Although radon can enter indoor air in buildings through its release from water from taps or during showering, the most significant source of radon in indoor air arises through natural accumulation from the environment. An evaluation of international research data (UNSCEAR, 2000) has concluded that, on average, 90% of the dose attributable to radon in drinking-water comes from inhalation rather than ingestion. Consequently, the setting of screening levels and guidance levels to limit the dose from ingestion of radon contained in drinking-water is not usually necessary. The screening measurements for gross alpha and gross beta activities will include the contribution from radon progeny, which is the principal source of dose from ingestion of radon present in drinking-water supplies. This is further discussed in section 9.7.

9.1 Sources[1] and health effects of radiation exposure

Radioactivity from several naturally occurring and human-made sources is present throughout the environment. Some chemical elements present in the environment are naturally radioactive. These are found in varying amounts in soils, water, indoor and outdoor air and even within our bodies, and so exposure to them is inevitable. In addition, Earth is constantly bombarded by high-energy particles originating both from the sun and from outside the solar system. Collectively, these particles are referred to as cosmic radiation. Everybody receives a dose from cosmic radiation, which is influenced by latitude, longitude and height above sea level.

The use of radiation in medicine for diagnosis and treatment is the largest human-made source of radiation exposure today. The testing of nuclear weapons, routine discharges from industrial and medical facilities and accidents such as Chernobyl have added human-made radionuclides to our environment.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2008) has estimated that the global average annual dose per person from all sources of radiation in the environment is approximately 3.0 mSv/year (see Box 9.1). Of this, 80% (2.4 mSv) is due to naturally occurring sources of radiation, 19.6% (almost 0.6 mSv) is due to the use of radiation for medical diagnosis and the remaining 0.4%

[1] When the term "source" appears in this chapter without any other reference, it is used in the context of "radiation source". For any other purpose, additional information is provided (e.g. "water source").

Box 9.1 Key terms, quantities and units

Becquerel (Bq)—The becquerel is the unit of radioactivity in the International System of Units (abbreviated SI from the French *Système international d'unités*), corresponding to one radioactive disintegration per second. In the case of drinking-water, it is usual to talk about the activity concentration, expressed in units of Bq/l.

Effective dose—When radiation interacts with body tissues and organs, the radiation dose received is a function of factors such as the type of radiation, the part of the body affected and the exposure pathway. This means that 1 Bq of radioactivity will not always deliver the same radiation dose. A unit called "effective dose" has been developed to take account of the differences between different types of radiation so that their biological impacts can be compared directly. The effective dose is expressed in SI units called sieverts (Sv). The sievert is a very large unit, and it is often more practical to talk in terms of millisieverts (mSv). There are 1000 mSv in 1 Sv.

Effective half-life—Radioisotopes have a "physical" half-life, which is the period of time it takes for one half of the atoms to disintegrate. Physical half-lives for various radioisotopes can range from a few microseconds to billions of years. When a radioisotope is present in a living organism, it may be excreted. The rate of this elimination is influenced by biological factors and is referred to as the "biological" half-life. The effective half-life is the actual rate of halving the radioactivity in a living organism as determined by both the physical and biological half-lives. Whereas for certain radionuclides, the biological processes are dominant, for others, physical decay is the dominant influence.

(around 0.01 mSv) is due to other sources of human-made radiation (see Figure 9.1). There can be large variability in the dose received by individual members of the population, depending on where they live, their dietary preferences and other lifestyle choices. Individual radiation doses can also differ depending on medical treatments and occupational exposures. Annual average doses and typical ranges of individual doses from naturally occurring sources are presented in Table 9.1 (UNSCEAR, 2008).

9.1.1 Radiation exposure through ingestion of drinking-water

Water sources can contain radionuclides of natural and artificial origin (i.e. human-made):

- Natural radionuclides, including potassium-40, and those of the thorium and uranium decay series, in particular radium-226, radium-228, uranium-234, uranium-238 and lead-210, can be found in water as a result of either natural processes (e.g. absorption from the soil) or technological processes involving naturally occurring radioactive materials (e.g. the mining and processing of mineral sands or phosphate fertilizer production).
- Human-made radionuclides may be present in water from several sources, such as
  - — radionuclides discharged from nuclear fuel cycle facilities;
  - — manufactured radionuclides (produced and used in unsealed form in medicine or industry) entered into drinking-water supplies as a result of regular or incidental discharges;
  - — radionuclides released in the past into the environment, including drinking-water sources.

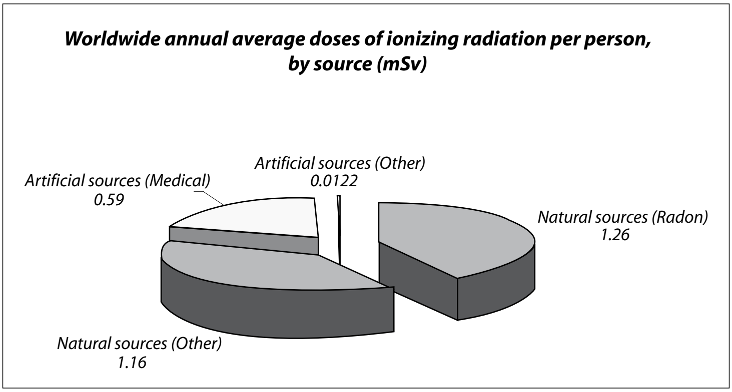


Figure 9.1 Distribution of average radiation exposure for the world population

Table 9.1 Average radiation dose from naturally occurring sources

Source	Worldwide average annual effective dose (mSv)	Typical annual effective dose range (mSv)
External exposure		
Cosmic rays	0.39	0.3–1[a]
Terrestrial radiation (outdoors and indoors)	0.48	0.3–1[b]
Internal exposure		
Inhalation (mainly radon)	1.26	0.2–10[c]
Ingestion (food and drinking-water)	0.29	0.2–1[d]
Total	**2.4**	**1–13**

[a] Range from sea level to high ground elevation.
[b] Depending on radionuclide composition of soil and building material.
[c] Depending on indoor accumulation of radon gas.
[d] Depending on radionuclide composition of foods and drinking-water.
Source: Adapted from UNSCEAR (2008)

9.1.2 Radiation-induced health effects through drinking-water

Radiation protection is based on the assumption that any exposure to radiation involves some level of risk. For prolonged exposures, as is the case for ingestion of drinking-water containing radionuclides over extended periods of time, evidence of an increased cancer risk in humans is available at doses above 100 mSv (Brenner et al., 2003). Below this dose, an increased risk has not been identified through epidemiological studies. It is assumed that there is a linear relationship between exposure and risk, with no threshold value below which there is no risk. The individual dose criterion (IDC) of 0.1 mSv/year represents a very low level of risk that is not expected to give rise to any detectable adverse health effect.

Box 9.2 Radiation exposure situations

The ICRP (2008) distinguishes between three types of radiation exposure situations—planned, existing and emergency exposure situations:

- A ***planned exposure*** situation is a situation that arises from the planned operation of a radiation source or from a planned activity that results in an exposure to a radiation source (e.g. exposure to a radiation source during a medical procedure for diagnosis or treatment).
- An ***existing exposure*** situation is a situation that already exists when a decision on the need for control has to be taken (e.g. exposure to indoor radon in dwellings).
- An ***emergency exposure*** situation is a situation that arises as a result of an accident, a malicious act or any other unexpected event. The present Guidelines do not apply during emergency exposure situations (see chapter 6).

Box 9.3 Individual dose criterion (IDC) and health risks

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:

- Individual doses from natural radioactivity in the environment vary widely. The average is about 2.4 mSv/year, but in some parts of the world, average doses can be up to 10 times higher (i.e. 24 mSv/year) without any observed increase in health risks, as noted in long-term population studies (Tao, 2000; Nair et al., 2009). An IDC of 0.1 mSv/year therefore represents a small addition to natural levels.
- The nominal risk coefficient for radiation-induced cancer incidence is 5.5×10^{-2}/Sv (ICRP, 2008). Multiplying this by an IDC of 0.1 mSv/year from drinking-water gives an estimated annual cancer risk of approximately 5.5×10^{-6}.

9.2 Rationale for screening levels and guidance levels

The current Guidelines are based on the approach proposed by the ICRP in situations of prolonged radiation exposure of the public. According to the ICRP, in planned exposure situations (see Box 9.2), it is prudent to restrict the prolonged component of the individual dose to 0.1 mSv in any given year (ICRP, 2000). It is recognized that exposure to radionuclides in drinking-water may be a consequence of a planned exposure situation, but is more likely to be from an existing exposure situation. Rather than adopt a different approach depending on whether or not the radionuclides are naturally occurring or human-made, a pragmatic and conservative approach was adopted, with an IDC of 0.1 mSv from 1 year's consumption of drinking-water, regardless of the origin of the radionuclides (see Box 9.3).

Screening levels and guidance levels are conservative and should not be interpreted as mandatory limits. Exceeding a guidance level should be taken as a trigger for further investigation, but not necessarily as an indication that the drinking-water is unsafe.

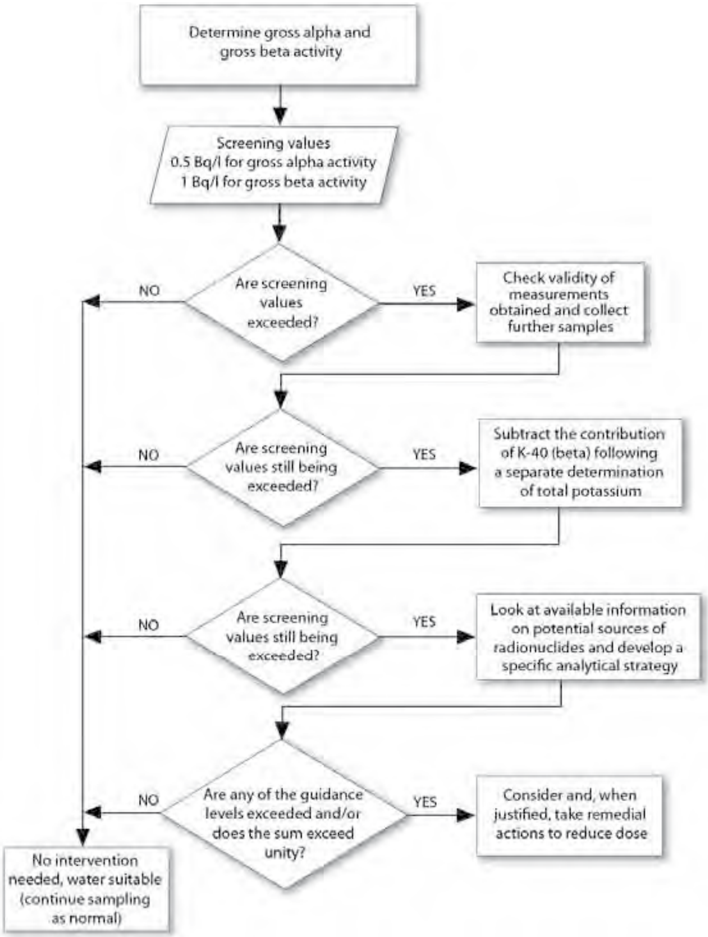


Figure 9.2 Application of screening and guidance levels for radionuclides in drinking-water

In the second edition of the Guidelines, the IDC of 0.1 mSv/year was based on screening levels for gross alpha activity and gross beta activity of 0.1 Bq/l and 1 Bq/l, respectively. This IDC represents less than 5% of the average annual dose attributable to radiation of natural origin (see section 9.1). Subsequent experience indicated that, in practice, the 0.1 mSv annual dose would usually not be exceeded if the gross alpha activity was equal to or below 0.5 Bq/l. For this reason, in the third edition of the Guidelines, the IDC was based on screening levels of 0.5 Bq/l for gross alpha activity and 1 Bq/l for gross beta activity. This change was carried forward to the current edition of the Guidelines.

9.3 Monitoring and assessment for dissolved radionuclides

The recommended assessment methodology for controlling radionuclide health risks from drinking-water is illustrated in Figure 9.2 and summarized in Box 9.4.

Box 9.4 Recommended assessment methodology

The recommended assessment methodology for controlling radionuclide health risks from drinking-water involves four steps:

1. An IDC[1] of 0.1 mSv from 1 year's consumption of drinking-water is adopted.
2. Initial screening is undertaken for both gross alpha activity and gross beta activity. If the measured activity concentrations are below the screening levels of 0.5 Bq/l for gross alpha activity and 1 Bq/l for gross beta activity, no further action is required.
3. If either of the screening levels is exceeded, the concentrations of individual radionuclides should be determined and compared with the guidance levels (see Table 9.2).
4. The outcome of this further evaluation may indicate that no action is required or that further evaluation is necessary before a decision can be made on the need for measures to reduce the dose.

9.3.1 Screening of drinking-water supplies

The process of identifying individual radionuclides in drinking-water and determining their concentration is time-consuming and expensive. Because, in most circumstances, the concentrations are low, such detailed analysis is normally not justified for routine monitoring. 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.

These measurements are suitable as a preliminary screening procedure to determine whether further radioisotope-specific analysis is necessary. They can also be used for detecting changes in the radiological characteristics of the drinking-water source as well as for identifying spatial and/or temporal trends in the radionuclide content of drinking-water.

Screening levels for drinking-water, below which no further action is required, are 0.5 Bq/l for gross alpha activity and 1 Bq/l for gross beta activity. If neither of these values is exceeded, the IDC of 0.1 mSv/year will also not be exceeded. The use of these screening levels is recommended, as this maximizes both the reliability and the cost-effectiveness of assessing the radionuclide content of drinking-water.

Radionuclides emitting low-energy beta activity, such as tritium, and some gaseous or volatile radionuclides, such as iodine, will not be detected by standard gross activity measurements. Routine analysis for these radionuclides is not necessary, but, if there are any reasons for believing that they may be present, radionuclide-specific sampling and measurement techniques should be used.[2]

Gross beta measurements include 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. If the screening level of 1 Bq/l for gross beta is exceeded, the contribution of potassium-40 to beta activity should be subtracted following a separate determination of total potassium. The

[1] In the European Commission Drinking Water Directive (European Commission, 2001), this parameter is called the total indicative dose (TID), and the same value of 0.1 mSv/year is adopted.

[2] References for analytical methods and treatment technologies specific to radionuclides are provided in Annex 6.

beta activity of potassium-40 is 27.9 Bq/g of stable potassium, which is the factor that should be used to calculate the beta activity due to potassium-40.

9.3.2 Strategy for assessing drinking-water if screening levels are exceeded

If either of the screening levels is exceeded, then the specific radionuclides should be identified and their individual activity concentrations measured. This will allow the contribution from each radionuclide to the IDC to be calculated. If the following additive formula is satisfied, then 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 = the guidance level (see Tables 9.2 and A6.1 in Annex 6) of radionuclide *i* that, at an intake of 2 litres/day[1] for 1 year, will result in an effective dose of 0.1 mSv/year.

If any of the guidance levels is exceeded, then the sum will exceed unity. The sum may also exceed unity even if none of the individual guidance levels is exceeded. Where the sum exceeds unity for a single sample, the IDC of 0.1 mSv/year would be exceeded only if the exposure to the same measured concentrations were to continue for a full year. *Hence, such a result does not in itself imply that the water is unsuitable for consumption.*

9.3.3 Strategy for assessing drinking-water if guidance levels are exceeded

An annual dose of 0.1 mSv is a small percentage of the average radiation dose received by any individual. Both the screening levels and guidance levels are highly conservative values that allow national authorities to determine, without further consideration, that the drinking-water is fit for consumption from a radiological viewpoint. National experiences have shown that the vast majority of water supplies comply with these criteria.

Occasionally, the situation may arise where the guidance levels are consistently exceeded for one or a combination of specific radionuclides. National authorities will then need to make a decision regarding the need to implement remedial measures or to place some restriction on the continued use of the water supply for drinking purposes.

From a radiological point of view, one of the key considerations is the extent to which the guidance levels are exceeded. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources address drinking-water in the chapter on existing exposure situations and contain a requirement that the highest annual individual doses received from the consumption of

[1] Where national or regional consumption rates are known, the guidance level should be adjusted to take this into account.

Table 9.2 Guidance levels for common[a] natural and artificial radionuclides

Category	Radionuclide	Dose coefficient (Sv/Bq)	Guidance level[b] (Bq/l)
Natural occurring radioactive isotope that starts the uranium decay series[c]	Uranium-238	4.5×10^{-8}	10
Natural occurring radioactive isotopes belonging to the uranium decay series	Uranium-234	4.9×10^{-8}	1
	Thorium-230	2.1×10^{-7}	1
	Radium-226	2.8×10^{-7}	1
	Lead-210	6.9×10^{-7}	0.1
	Polonium-210	1.2×10^{-6}	0.1
Natural occurring radioactive isotope that starts the thorium decay series	Thorium-232	2.3×10^{-7}	1
Natural occurring radioactive isotopes belonging to the thorium decay series	Radium-228	6.9×10^{-7}	0.1
	Thorium-228	7.2×10^{-8}	1
Artificial radionuclides that can be released to the environment as part of the fission products found in reactor emissions or nuclear weapons tests	Caesium-134[d]	1.9×10^{-8}	10
	Caesium-137[d]	1.3×10^{-8}	10
	Strontium-90[d]	2.8×10^{-8}	10
Artificial radionuclide that can be released to the environment as a fission product (see above). It is also used in nuclear medicine procedures and thus can be released into water bodies through sewage effluent.	Iodine-131[d,e]	2.2×10^{-8}	10
Radioactive isotope of the hydrogen produced artificially as a fission product from nuclear power reactors and nuclear weapons tests. It may be naturally present in the environment in a very small amount. Its presence in a water source suggests potential industrial contamination.	Tritium[e]	1.8×10^{-11}	10 000
Naturally occurring radioactive isotope widely distributed in nature and present in organic compounds and in the human body.	Carbon-14	5.8×10^{-10}	100
Artificial isotope formed in nuclear reactors that also exists in trace quantities in *natural* uranium ores.	Plutonium-239[d]	2.5×10^{-7}	1
Artificial isotope by-product formed in nuclear reactors.	Americium-241[d]	2.0×10^{-7}	1

[a] This list is not exhaustive. In certain circumstances, other radionuclides should be investigated (see Annex 6).

[b] Guidance levels were rounded to the nearest order of magnitude by averaging the log scale values (to 10n if the calculated value was below 3×10^n and to 10^{n+1} if value was 3×10^n or above). For example, if the calculated value was 2 Bq/L (i.e. 2×10^0), the guidance level was rounded to 10^0 (i.e. = 1) whereas. if the calculated value was 3 Bq /L, (i.e. 3×10^0 or above) the guidance level was rounded to 10^1 (i.e. = 10).

[c] Separate guidance levels are provided for individual uranium radioisotopes in terms of radioactivity (i.e. expressed as Bq/l). The provisional guideline value for total content of uranium in drinking-water is 30 µg/l based on its chemical toxicity, which is predominant compared with its radiological toxicity (see chapter 12).

[d] These radionuclides either may not occur in drinking-water in normal situations or may be found at doses that are too low to be of significance to public health. Therefore, they are of lower priority for investigation following an exceedance of a screening level.

[e] Although iodine and tritium will not be detected by standard gross activity measure¬ments and routine analysis for these radionuclides is not necessary, if there are any reasons for believing that they may be present, radionuclide-specific sampling and measurement tech¬niques should be used. This is the reason for including them in this table.

drinking-water do not exceed a value of approximately 1 mSv.[1] This should not be regarded either as an "acceptable" dose or as a dose limit, and all reasonable efforts should be made to minimize the doses received. Each situation will be different, and non-radiological factors, such as the costs of remediation and the availability of other drinking-water supplies, will need to be taken into account in reaching a final decision. National authorities also need to be aware that radionuclides such as uranium are chemically toxic, and the allowable concentrations in drinking-water may be determined by a radioisotope's toxicological rather than its radioactive properties (see chapter 12).

9.3.4 Sampling frequency

Criteria for monitoring radiological contamination of drinking-water should be developed, taking into account available resources and the potential for radiological risks. It should not detract from the adequate assessment and management of microbial and chemical risks. New water supplies should be sampled to determine their suitability for drinking-water, whereas existing supplies would need monitoring occasionally. If the water supply is adequately characterized and measured concentrations are consistently below screening levels, then sampling frequency should be reduced. However, if sources of potential radionuclide contamination exist nearby or are expected to be changing rapidly with time, then the sampling should be more frequent. Sampling frequency should be maintained, or even increased, if concentrations are approaching the screening levels or if the sum of ratios of the observed concentrations of individual radionuclides to their guidance levels approaches unity (see below). A graded approach to sampling frequency should be developed commensurate with the degree of contamination, the source of supply (i.e. surface water or groundwater), the size of the population served, the expected variability of radionuclide concentrations and the availability and results of historical monitoring records. International standards are available relating to the assessment of radiological water quality, including sampling procedures (e.g. preservation and handling of samples) and programmes (Standards Australia & Standards New Zealand, 1998; ISO, 2003, 2006a,b, 2009a).

9.4 Guidance levels for radionuclides commonly found in drinking-water

Guidance levels established for naturally occurring and human-made radionuclides most commonly detected in drinking-water supplies as well as for human-made radionuclides potentially relevant for prolonged exposure situations resulting from past nuclear emergency situations are presented in Table 9.2. The respective dose coefficients for adults are also presented (IAEA, 1996; ICRP, 1996).

The guidance level for each radionuclide in Table 9.2 represents the concentration that, if present in the drinking-water consumed throughout the year, would result in an individual dose of 0.1 mSv.

The guidance levels were calculated using dose coefficients for adults. Insufficient evidence was found to introduce separate guidance levels for different age groups. Although infants and children consume a lower mean volume of drinking-water, the

[1] IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (revised edition, in preparation).

age-dependent dose coefficients for children are higher than those for adults, accounting for higher uptake or metabolic rates. In the case of prolonged contamination of the water source, an assessment of doses to infants and children may be considered.

The guidance levels apply to routine ("normal") operational conditions of existing or new drinking-water supplies. They do not apply during an emergency exposure situation involving the release of radionuclides into the environment. However, the guidance levels apply again once the relevant authorities have declared an end to the emergency exposure situation. Additional guidance is provided in section 6.7 and in several publications (IAEA, 2002; IAEA & WHO, 2005, 2010; ICRP, 2009a).

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

$$GL = \frac{IDC}{h_{ing} \times q}$$

where:

- GL = guidance level of radionuclide in drinking-water (Bq/l)
- 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 (equivalent to the standard World Health Organization drinking-water consumption rate of 2 litres/day)

9.5 Analytical methods

9.5.1 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 high total dissolved solids (TDS) content. Where possible, standardized methods should be used to determine concentrations of gross alpha and gross beta activities. Procedures for this analysis are listed in Table 9.3.

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 et al., 2005) 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.

9.5.2 Measuring specific radionuclides

If either of the gross alpha and gross beta screening levels is exceeded, then the specific radionuclides should be identified and their individual activity concentrations measured.

Table 9.3 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 9696 for gross alpha (ISO, 2007) ISO 9697 for gross beta (ISO, 2008) ISO 10704 for gross alpha and gross beta (ISO, 2009b)	Evaporation	0.02–0.1 Bq/l	Groundwater with TDS less than 0.1 g/l
American Public Health Association (APHA et al., 2005)	Co-precipitation	0.02 Bq/l	Surface water and groundwater (TDS is not a factor)

References for analytical methods for specific radionuclides are provided in Annex 6. Information on measuring radon concentrations in water is provided in section 9.7.4.

9.6 Remedial measures

If the IDC of 0.1 mSv/year is being exceeded, then the options available to the regulatory 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). Any decision that alters the radiation exposure situation should do more good than harm. This means that by reducing existing exposure, it will achieve sufficient individual or societal benefit to offset the detriment it causes (ICRP, 2008).

Once the remedial action is justified, then protection should be optimized in accordance with the recommendations of ICRP (2008). The principle of optimization of protection implies that the likelihood of incurring exposures, the number of people exposed and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking economic and societal factors into account.

When source water contains unacceptably high concentrations of radionuclides, control options include use of an alternative supply, controlled blending with another source or additional water treatment. Treatment plants with a combination of coagulation, sedimentation and sand filtration processes may remove up to 100% of the suspended radioactivity present in raw waters. Lime–soda ash softening plants can also remove practically all of the suspended radioactivity, depending on the radionuclide and on the proportion of radioactivity that might be associated with particulates.

A comprehensive review of the removal of dissolved radionuclides by water treatment processes has been undertaken (Brown, Hammond & Wilkins, 2008). The results summarized in that report are reproduced in Table 9.4. References for treatment technologies specific to radionuclides are provided in Annex 6.

9.7 Radon

9.7.1 Radon in air and water

Uranium, radium and radon are all soluble in water. Radon present in surface waters, such as lakes and rivers, is readily released into outdoor air by agitation as it passes

Table 9.4 Treatment performance for some common radionuclides[a]

Element	Coagulation	Sand filtration	Activated carbon	Precipitation softening	Ion exchange	Reverse osmosis
Strontium	xx	xx	x	xxxx	xxx	xxxx
Iodine	xx	xx	xxx	x	xxx	xxxx
Caesium	xx	xx	x	xx	xxx	xxxx
Radium	xx	xxx	xx	xxxx	xxxx	xxxx
Uranium	xxxx	x	xx	xxxx	xxxx	xxxx
Plutonium	xxxx	xx	xxx	x	xxxx	xxxx
Americium	xxxx	xx	xxx	x	xxxx	xxxx
Tritium	Not possible to remove					

[a] x = 0–10% removal; xx = 10–40% removal; xxx = 40–70% removal; xxxx = > 70% removal.

Box 9.5 Radon in drinking-water

- Some groundwater supplies may contain elevated concentrations of radon. High radon concentrations are seldom found in surface drinking-water supplies.
- Radon dissolved in drinking-water can be released into indoor air. Normally, a higher radon dose is received from inhaling the radon and radon progeny compared with their ingestion.
- Radon released from drinking-water is not the only source of radon in indoor air. Where high indoor radon concentrations exist, the underlying soil and building materials, rather than the drinking-water, are normally the predominant sources.
- Straightforward and effective techniques exist to reduce the concentration of radon in drinking-water supplies.
- In deciding whether or not to take steps to reduce the concentration of radon in drinking-water supplies, it is important to take account of the contribution of other sources of radon to the total radiation dose. Any action should be both justified and optimized and take account of local conditions.

over rocks and soils. Groundwater from wells and boreholes usually contains higher radon concentrations than surface waters. In some extreme circumstances, very high radon concentrations can be found in drinking-water supplies from these sources (see Box 9.5).

Radon is soluble in water, its solubility decreasing rapidly with an increase in temperature. When a tap or shower is turned on, some of the dissolved radon is released into indoor air. This adds to the radon present from other sources and will give rise to a radiation dose when inhaled.

An evaluation of international research data (UNSCEAR, 2000) has concluded that, on average, 90% of the dose attributable to radon in drinking-water comes from inhalation rather than ingestion. Therefore, controlling the inhalation pathway rather than the ingestion pathway is the most effective way to control doses from radon in drinking-water.

The percentage of radon present in drinking-water that is released into indoor air will depend on local conditions, such as the total consumption of water in the house, the volume of the house and its ventilation rate, and is likely to be highly variable. It has been estimated that a radon concentration of 1000 Bq/l in drinking-water discharged from a tap or shower will, on average, increase the radon concentration by 100 Bq/m^3 in indoor air (NAS, 1999; European Commission, 2001; Health Canada, 2009). This contribution is not constant, as it occurs only while the water is being discharged through the tap or shower. Radon in air also comes from other sources, in particular radon entering the home from the underlying soil.

9.7.2 Health risks from radon

Epidemiological studies have clearly shown that long-term exposure to high radon concentrations in indoor air increases the risk of lung cancer (WHO, 2009). Radon ingested in drinking-water will give a radiation dose to the lining of the stomach. Scientific studies have not shown a definitive link between consumption of drinking-water containing radon and an increased risk of stomach cancer (Ye et al., 1998; Auvinen et al., 2005; WHO, 2009).

9.7.3 Guidance on radon in drinking-water supplies

As the dose from radon present in drinking-water is normally received from inhalation rather than ingestion, it is more appropriate to measure the radon concentration in air than in drinking-water.

The World Health Organization reference level for radon concentration in indoor air is 100 Bq/m^3 in dwellings. If this level cannot be reached under prevailing country-specific conditions, the level should not exceed 300 Bq/m^3, corresponding to an annual dose of approximately 10 mSv (WHO, 2009). This recommendation is consistent with the International Basic Safety Standards[1] and with the most recent recommendations of the ICRP (2009b).

Screening levels for radon in water should be set on the basis of the national reference level for radon in air and the distribution of radon in the national housing stock. Where high radon concentrations are identified in indoor air, this is nearly always due to ingress of radon from the soil rather than degassing from the drinking-water supply. Nevertheless, in circumstances where high radon concentrations might be expected in drinking-water, it is prudent to measure for radon and, if high concentrations are identified, consider whether measures to reduce the concentrations present are justified.

The concentration of radon in groundwater supplies can vary considerably. Consequently, in situations where high radon concentrations have been identified or are suspected, the frequency of gross alpha and gross beta measurements may need to be increased so that the presence of radon progeny (in particular polonium-210), which can be major contributors to dose, can be assessed and monitored on an ongoing basis.

[1] International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (revised edition, in preparation).

9.7.4 Measuring radon in drinking-water

There are difficulties in deriving activity concentrations of radon in drinking-water because of the ease with which radon is released from water during handling. Stirring and transferring water from one container to another will release dissolved radon. Water that has been left to stand will have reduced radon activity, and boiling will also completely release radon from the water into the air. A variety of methods can be used to measure radon in water, including liquid scintillation counting, which is a sensitive and widely used method (WHO, 2009).

9.7.5 Decreasing radon concentrations in drinking-water

Reasonably simple measures are available to decrease radon concentrations in drinking-water by aeration. High-performance aeration is an effective means for the removal of radon in groundwater supplies and can achieve up to 99.9% removal. However, these methods may create a large source of airborne radon. Adsorption via granular activated carbon, with or without ion exchange, can also achieve high radon removal efficiencies, but is less efficient and requires large amounts of granular activated carbon.

9.8 Risk communication

9.8.1 Reporting results

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

- sample identification code;
- sample collection date and time;
- standard analytical methods used or brief description of any non-standard analytical methods used;
- identification of the radionuclides or type of radioactivity and total radioactivity determined;
- measurement-based concentration or activity value calculated using the appropriate blank for each radionuclide;
- estimates of the counting uncertainty;
- a minimum detectable concentration for each radionuclide or parameter analysed;
- estimate of total projected uncertainty of the reported result, including the contributions from all the parameters within the analytical method (i.e. counting and other random and systematic uncertainties or errors).

9.8.2 Communicating risks

Communicating radiation risks clearly and effectively includes identifying target audiences (e.g. public, policy-makers and decision-makers) and tailoring the messages to them (WHO, 2002). Risk has different meaning for different people, but, in general, risk communication requires a description of the likelihood of harm and its severity.

Risk communication with the public should utilize plain language. The technical lexicon of radiation protection is not readily understood by non-specialists (Picano, 2008). In some situations, comparisons are helpful to explain radiation risks (e.g. placing possible health risks from ingestion of drinking-water in the context of risk associated with exposure to natural radiation in different parts of the world). It should be clearly explained that guidance levels should not be interpreted as mandatory limits and that exceeding a guidance level may be taken as a trigger for further investigation, but it is not necessarily an indication that the drinking-water is unsafe.

The persons in charge of communicating risk should be skilled in interpersonal communication, able to convey empathy, effective listeners and respectful of people's concerns. They should be knowledgeable about the topic area with which they are dealing and be able to answer basic questions about the current as well as possible future risks. Guidance on radiation risk communication is provided elsewhere (USEPA, 2007; WHO, 2009).