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Measurement of radioactivity in the environment — Guidelines for effective dose assessment using environmental monitoring data —

Part 1: Planned and existing exposure situation

Mesurage de la radioactivité dans l'environnement — Lignes directrices pour l'évaluation de la dose efficace à l'aide de données de surveillance environnementale —

Partie 1: Situation d'exposition existante et planifiée

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Foreword

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

A list of all the parts in the ISO 20043 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Everyone is exposed to natural radiation. The natural sources of radiation are cosmic rays and naturally occurring radioactive substances existing in the Earth itself and inside the human body. Human activities involving the use of radiation and radioactive substances (NORM) cause radiation exposure in addition to the natural exposure. Some of those activities, such as the mining and use of ores containing naturally-occurring radioactive substances and the production of energy by burning coal that contains such substances, simply enhance the exposure from natural radiation sources. Nuclear installations use radioactive materials and produce radioactive effluent and waste during operation and on their decommissioning. The use of radioactive materials in industry, agriculture and research is expanding around the globe.

All these human activities generally also give rise to radiation exposures that are only a small fraction of the global average level of natural exposure. The medical use of radiation is the largest and a growing man-made source of radiation exposure in developed countries. It includes diagnostic radiology, radiotherapy, nuclear medicine and interventional radiology.

Radiation exposure also occurs as a result of occupational activities. It is incurred by workers in industry, medicine and research using radiation or radioactive substances, as well as by passengers and crew during air travel and for astronauts. The average level of occupational exposures is generally similar to the global average level of natural radiation exposure[1].

As the uses of radiation increase, so do the potential health risks and the public's concerns increase. Thus, all these exposures are regularly assessed in order to

a) improve the understanding of global levels and temporal trends of public and worker exposure,

b) evaluate the components of exposure so as to provide a measure of their relative importance, and

c) identify emerging issues that may warrant more attention and scrutiny. While doses to workers are usually directly measured, doses to the public are usually assessed by indirect methods using radioactivity measurement results performed on various sources: waste, effluent and/or environmental samples.

To ensure that the data obtained from radioactivity monitoring programs support their intended use, it is essential in the dose assessment process that stakeholders (the operators, the regulatory bodies, the local information committee and associations, etc.) agree on appropriate data quality objectives, methods and procedures for: the sampling, handling, transport, storage and preparation of test samples; the test method; and for calculating measurement uncertainty. An assessment of the overall measurement uncertainty also needs to be carried out systematically. As reliable, comparable and 'fit for purpose' data are an essential requirement for any public health decision based on radioactivity measurements, international standards of tested and validated radionuclide test methods are an important tool for the production of such measurement results. The application of standards serves also to guaranty comparability over time of the test results and between different testing laboratories. Laboratories apply them to demonstrate their technical competences and to complete proficiency tests successfully during interlaboratory comparisons, two prerequisites to obtain national accreditation.

Today, over a hundred international standards, prepared by Technical Committees of the International Organization for Standardization, including those produced by ISO/TC 85 working groups, and the International Electrotechnical Commission, are available for measuring radionuclides in different matrices by testing laboratories.

Generic standards help laboratories to manage the measurement process and specific standards describing test methods are used specifically by those in charge of radioactivity measurement. These later cover test methods for:

— Natural radionuclides, including ^{40}K, ^{3}H, ^{14}C and those originating from the thorium and uranium decay series, in particular ^{226}Ra, ^{228}Ra, ^{234}U, ^{238}U, ^{220}Rn, ^{222}Rn, ^{210}Pb, which can be found in every material from natural sources or can be released from technological processes involving naturally

occurring radioactive materials (e.g. the mining and processing of mineral sands or phosphate fertilizer production and use), and

— Man-made radionuclides, such as transuranium elements (americium, plutonium, neptunium, and curium), ^{3}H, ^{14}C, ^{90}Sr and gamma emitting radionuclides found in waste, liquid and gases effluent and in environmental matrices (air, soil, water, biota) as a result of authorized releases into the environment and of fallout resulting from the explosion in the atmosphere of nuclear devices and accidents, such as those that occurred in Chernobyl and Fukushima. Radionuclides, such as ^{3}H and ^{14}C occur both naturally and as by-products of the operation of nuclear reactors.

The ICRP recognises three types of exposure situations[2] that are intended to cover the entire range of exposure situations: planned, emergency and existing exposure situations. Planned exposure situations involve the planned introduction and operation of sources (previously categorised as practices). Emergency exposure situations are situations requiring prompt action in order to avoid or to reduce adverse consequences. Existing exposure situations are exposure situations that already exist when a decision on control is taken, such as those caused by enhanced natural background radiation (e.g. exposure to radon in existing buildings).

The fraction of the background dose rate to man from environmental radiation, mainly gamma radiation, is very variable and depends on factors such as the radioactivity of the local rock and soil, the nature of building materials and the construction of buildings in which people live and work.

This document sets out principles and guidance for the radiological characterisation of the environment needed for checking the results of

— prospective assessment of dose to the public arising from exposure to ionizing radiation which may arise from planned discharges to the atmosphere and to the aquatic environment or following remediation action;

— retrospective assessment for dose that may be made for discharges or disposals that were not initially covered by an authorization/permit delivered by a national regulatory body (e.g. contaminated land or dose associated with accidental releases of radionuclides into the environment).

This document is one of a set of generic ISO Standards on measurement of radioactivity.

Example of dose assessment in different exposure situations, modified from Reference [3]

Situation	Type of assessment	
	Prospective	Retrospective
Planned	Determining compliance with the relevant dose constraint (dose limit or regulatory requirements). A prospective assessment includes the exposures expected to occur in normal operation.	Estimating dose to the public from past operations
Existing	Future prolonged exposures (e.g. after remediation)	Past exposures (e.g. occupancy of contaminated lands)
Emergency	Emergency planning (operational intervention level)	Actual impacts after emergency

Measurement of radioactivity in the environment — Guidelines for effective dose assessment using environmental monitoring data —

Part 1: Planned and existing exposure situation

1 Scope

These international guidelines are based on the assumption that monitoring of environmental components (atmosphere, water, soil and biota) as well as food quality ensure the protection of human health[2][4][5][6][7][8]. The guidelines constitute a basis for the setting of national regulations and standards, *inter alia*, for monitoring air, water and food in support of public health, specifically to protect the public from ionizing radiation.

This document provides

— guidance to collect data needed for the assessment of human exposure to radionuclides naturally present or discharged by anthropogenic activities in the different environmental compartments (atmosphere, waters, soils, biological components) and food;

— guidance on the environmental characterization needed for the prospective and/or retrospective dose assessment methods of public exposure;

— guidance for staff in nuclear installations responsible for the preparation of radiological assessments in support of permit or authorization applications and national authorities' officers in charge of the assessment of doses to the public for the purposes of determining gaseous or liquid effluent radioactive discharge authorizations;

— information for the public on the parameters used to conduct a dose assessment for any exposure situations to a representative person/population. It is important that the dose assessment process be transparent, and that assumptions are clearly understood by stakeholders who can participate in, for example, the selection of habits of the representative person to be considered.

Generic mathematical models used for the assessment of radiological human exposure are presented to identify the parameters to monitor, in order to select, from the set of measurement results, the "best estimates" of these parameter values. More complex models are often used that require the knowledge of supplementary parameters.

The reference and limit values are not included in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

ISO 80000-10, *Quantities and units — Part 10: Atomic and nuclear physics*

3 Terms and definitions

For the purposes of this document, the definitions given in ISO 80000-10, ISO/IEC Guide 98-3, ISO/IEC Guide 99, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
background
doses, dose rates or activity concentrations associated with natural sources, or any other sources in the environment that are not amenable to control

3.2
conversion coefficient
coefficient giving effective dose in an external exposure

3.3
data quality objectives
statement of the required detection limits, accuracy, reproducibility and repeatability of the required analytical and other data

Note 1 to entry: Generic data quality objectives can sometimes be set at national level. Data quality objectives can also embrace an amount of data required for an area of land (or part of a site) to enable sound comparison with generic guidelines or standards or for a site-specific or material-specific estimation of risk.

3.4
dose assessment
assessment of the dose(s) to an individual or group of people

Note 1 to entry: For example, assessment of the dose received or committed by an individual on the basis of results from workplace monitoring or bioassay.

Note 2 to entry: the term exposure assessment is also sometimes used.

3.5
dose coefficient
coefficient giving the committed effective dose from an internal exposure

3.6
emergency exposure situations
situation of exposure arising as a result of an accident, a malicious act or other unexpected event that requires prompt action in order to avoid or to reduce adverse consequences

3.7
existing exposure situations
situation of exposure that already exists when a decision on the need for control needs to be taken

Note 1 to entry: Existing exposure situations include exposure to natural background radiation that is amenable to control; exposure due to residual radioactive material that derives from past practices (3.13) that were never subject to regulatory control; and exposure due to residual radioactive material deriving from a nuclear or radiological emergency after an emergency has been declared to be ended.

3.8
hazard
potential for harm or detriment, especially for radiation risks; a factor or condition that might operate against safety

3.9
intended use
use in accordance with information provided with a product or system, or, in the absence of such information, by generally understood patterns of usage

3.10
model
analytical representation or quantification of a real system and the ways in which phenomena occur within that system, used to predict or assess the behaviour of the real system under specified (often hypothetical) conditions

[SOURCE: IAEA Safety Standard No. RS-G-1.8]

3.11
monitoring
measurement of dose, dose rate or activity for reasons relating to the assessment or control of exposure to radiation or exposure due to radioactive substances, and the interpretation of the results

[SOURCE: IAEA Safety Glossary Terminology used in Nuclear Safety and Radiation Protection – 2018 Edition]

3.12
planned exposure situations
situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure due to a source

[SOURCE: IAEA Safety Glossary Terminology used in Nuclear Safety and Radiation Protection – 2018 Edition]

3.13
practice
human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed

[SOURCE: IAEA Safety Standard No. RS–G–1.8]

3.14
quality assurance
planned and systematic actions necessary to provide adequate confidence that an item, process or service satisfy given requirements for quality, for example, those specified in the license

[SOURCE: IAEA Safety Standard No. RS-G-1.8]

3.15
radioactive discharges
radioactive substances arising from a source (3.22) within a practice (3.13) which are discharged as gases, aerosols, liquids or solids to the environment, generally with the purpose of dilution and dispersion or disposal

[SOURCE: IAEA Safety Standard No. RS-G-1.8]

3.16
representative person
individual receiving a dose that is representative of the doses to the more highly exposed individuals in the population

[SOURCE: ICRP Publication 101a. Annuals of the ICRP, 2006]

3.17
risk
combination of the probability of occurrence of harm and the severity of that harm

Note 1 to entry: The probability of occurrence includes the exposure to a hazardous situation, the occurrence of a hazardous event and the possibility to avoid or limit the harm.

3.18
risk assessment
overall process comprising a risk analysis and a risk evaluation

3.19
screening
type of analysis aimed at eliminating from further consideration factors that are less significant for protection or safety, in order to concentrate on the more significant factors

3.20
site
defined area, in this context often local target area

3.21
soil
surface layer of the Earth's crust composed of mineral particles, including organic matter

3.22
source
anything that may cause radiation exposure, such as by emitting ionization or radiation or by relating radioactive substances or materials, and can be treated as a single entry for protection and safety purposes

Note 1 to entry: For example, materials emitting radon are sources in the environment, a sterilization gamma irradiation unit is a source for the practice (3.13) of radiation preservation of food, an X ray unit may be a source for the practice (3.13) of radiodiagnosis; a nuclear power plant is part of the practice (3.13) of generating electricity by nuclear fission, and may be regarded as a source (e.g. with respect to discharges to the environment) or as a collection of sources (e.g. for occupational radiation protection purposes). A complex or multiple installation situated at one location or site may, as appropriate, be considered a single source for the purposes of application of safety standards.

[SOURCE: IAEA Safety Standard No. RS-G-1.8]

3.23
surface soil
upper part of a natural soil, generally dark-coloured and with a higher content of organic substances and nutrient when compared to the subsoil below

3.24
surface water
lakes, ponds, impounding reservoirs, springs, flowing (streaming) waters, estuaries, wetlands, inlets, canals, oceans within the relevant territorial limits, and all other bodies of water, natural or artificial, inland or coastal, fresh or salt

4 Symbols

$\bar{A}_r^a(t)$	$\bar{A}_r(t_0+1)$ [average activity concentration in air a of a radionuclide r during a year from t_0+1 in Bq·m^{-3}
E	annual effective dose in Sv
E_{ext}	annual effective dose of representative individual due to external exposure in Sv
E_{ing}	committed effective dose of representative individual due to ingestion in Sv
E_{inh}	committed effective dose of representative individual due to inhalation in Sv
$E_{ext,\,air}$	an external exposure of airborne radionuclides in air
$E_{ext,\,soil}$	an external exposure of airborne radionuclides deposited on soil surface
$E_{inh,\,T}(t_1)$	age dependent committed equivalent dose in tissue or organ, T, due to the inhalation of air during a year t_1;
$g_{ing,r}$	age dependent committed effective dose coefficient from radionuclide, r, by ingestion in Sv·Bq^{-1}
$g_{inh,r}$	age dependent committed effective dose coefficient from radionuclide, r, by inhalation in Sv·Bq^{-1}
$g_{ing,r,T}$	age dependent committed equivalent dose coefficient in tissue or organ, T, from radionuclide, r, by ingestion in Sv·Bq^{-1}
$g_{inh,r,T}$	age dependent committed equivalent dose coefficient in tissue or organ, T, from radionuclide, r, by inhalation in Sv·Bq^{-1}
$\dot{H}^*(10,t)$	annual average ambient gamma dose-equivalent rate at 10 mm depth in Sv·h^{-1}
$H_{T,\,ext}$	committed equivalent dose in tissue or organ, T, in Sv
$H_{T,\,ing}$	committed equivalent dose in tissue or organ, T, from ingestion in Sv
$H_{T,\,inh}$	committed equivalent dose in tissue or organ, T, from inhalation in Sv
r	a given radionuclide part of a dose assessment
$\dot{V}$	age dependent breathing rate during a year in m^3·year^{-1}
w_T	tissue or organ weight factor

5 Principle

Radioactivity is a natural phenomenon common to every part of our environment and we are continuously exposed to these natural sources of radiation. Radiation and radioactive substances have many applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation health risks to workers and the public and the impact on the environment that may arise from these applications are assessed and, when necessary, controlled.

The aim of the health risk assessment of radioactive releases (authorized or accidental) from a nuclear installation into the environment is to estimate the potential health consequences of human exposure to radiation. The impact could be local, regional or worldwide, and can result from existing, planned or nuclear emergency exposures. These assessments are performed to identify the needs and priorities to ensure public health protection and to inform national authorities (decision makers) and the public.

Health risk assessment requires an estimation of radiation doses to the public that usually cannot be measured directly. Therefore, for the purpose of protection of the public health, it is necessary to characterise an individual, either hypothetical or specific. This individual is defined as the 'representative person'.

In the case of prospective assessment, for estimating the impact of future liquid or gaseous discharges from a particular emitter such as a nuclear facility, national regulations generally require dose calculations to be carried out, based on the maximal foreseen quantities of radionuclides to be released and considering conservative but realistic assumptions for determining the resulting quantities of

radionuclides in different compartments of the environment and then for calculating the effective dose received by the representative person.

Complementarily to this approach, once the aforementioned facility is in operation, measurements of the real activity concentrations of radionuclides in different compartments of the environment can be carried out so as to check that they remain below those that were expected during the initial assessment, and the dose assessment of the facility can be calculated as it relates to actual liquid and gaseous discharges of the facility. In addition, radioactivity measurements in all the affected compartments of the environment can help to confirm or to acquire useful information on mechanisms of transfer of radionuclides in the environment, which is essential for enhancing robustness or for building confidence in the dose assessment.

Finally, dose calculations can also be carried out directly from the results of radioactivity measurements in the environment to determine the dose arising from exposure pathway.

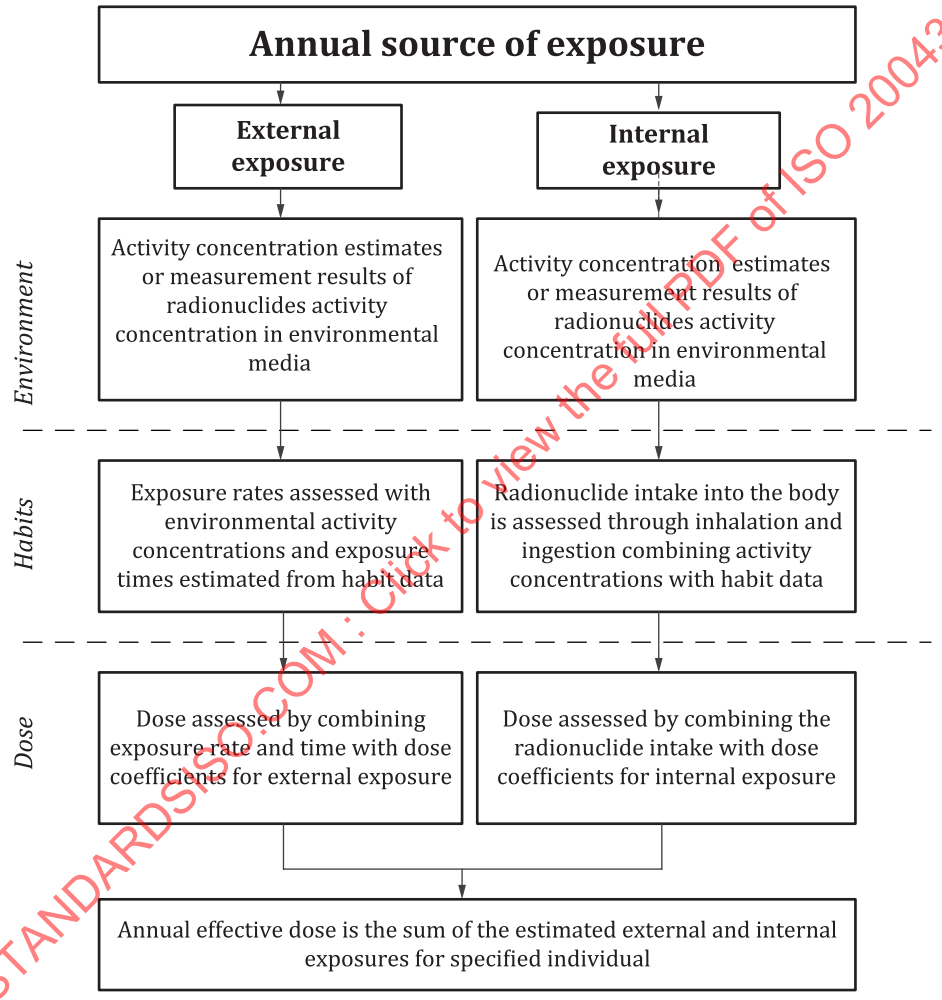

Figure 1 — Annual dose assessment process for specified individual modified from ICRP Publ. 101[3]

Dose assessment is a multistage process (see Figure 1) that follows the following stages:

— source identification and characterization, including data on the types and quantities of radionuclides and radiations emitted;

— environmental characterization, such as meteorological condition, type of biota, agricultural production, etc. and the activity concentration of radionuclides in environmental media and food arising from the source under investigation;

— exposure scenario identification and characterization to combine environmental activity concentration with habit data of the representative person (for example locations, ages, diets of the exposed individuals or population);

— dose calculation using dose coefficients that either relate to activity concentration in air or soil to external dose rates (external doses), or that convert a unit of intake of radionuclides through water and food into dose (internal doses);

— effective dose calculation by summing up the contributions from external and internal dose.

An exposure assessment is the process by which the intensity, frequency and duration of human exposure to a radionuclide are estimated. It is usually performed using one or more defined scenarios, and on the basis of the data connected with a specific site.

Thus, depending on the scenario, different environmental pathways to a representative individual are identified in order to determine the relevant activity concentration measurement of radionuclides in a variety of environmental media.

The effective dose to the representative person may be calculated either following a deterministic or a probabilistic approach, or a mixture of both approaches may be applied (see ICRP Pub101[3]). The method used depends on the situation, the capabilities and the data available. A brief description of these approaches follows.

Deterministic and probabilistic methods may not necessarily yield mathematically equivalent results.

The simplest deterministic method for the assessment of compliance is a screening evaluation. This method typically makes use of simplifying assumptions that lead to a very conservative estimate of dose based on, for example, activity concentration of radionuclides at the point of discharge from the source. Another simplifying assumption is to consider a single age group (e.g. adult) in estimating dose to the public to compare with the dose constraints (ICRP, 2000). If the results of relatively conservative screening assessments demonstrate that doses are well below the relevant dose constraint, there may be no need for further detailed assessment of dose. A number of screening methods have been developed and are available for application[3].

In another form of the deterministic method, a general assessment of the involved populations, pathways, and radionuclides is made with the goal of identifying the group or groups receiving higher doses using expert opinion, measurement data, or simple calculations. In some situations, people receiving the higher doses are easily identified because site-specific exposure data are readily available and habit information is known. In other situations, identifying these individuals is an iterative process that considers key pathways of exposure and populations receiving doses from the source. The iterative process usually indicates the areas that are likely to receive the greatest exposure from each pathway. These areas should be investigated in more detail. Ultimately, an individual/group is identified that is expected to receive the highest exposure taking all pathways into account. The mean dose to this individual/group is compared with the dose constraint to determine compliance. This method is the same as the critical group approach recommended previously by the ICRP.

The probabilistic method combines the distribution of values for parameters into a composite distribution that presents a range of possible doses based on their probability of occurrence. The distribution of calculated dose incorporates

a) the variability and uncertainty in the estimated environmental media activity concentration (i.e. radionuclide activity concentration in air, water, soil) and food;

b) variability and uncertainty in the habit data (i.e. breathing rate, food and water ingestion rates, time spent at various activities). As with the deterministic methods, identification of the exposed population and the exposure scenarios of concern are likely to be an iterative process. However, decision makers need guidance on how to determine compliance with the ICRP recommendations when probabilistic methods are used.

A mixture of the deterministic and probabilistic methods is often used. One example of this is the use of measurement data in an existing exposure situation to determine dose to individuals[9]. In this case, a

distribution of doses is produced because of the variability and uncertainty of habit and measurement data, and this distribution becomes the basis for determining compliance.

This document deals with the environmental monitoring stage on the activity concentration measurement of radionuclides in environmental media and includes the elements of the pathway exposure to assess either the total exposure of a given representative individual at risk, or the additional exposure from a given source or activity.

Characterization of sites with respect to external and internal exposure pathways is described in Clause 6, description of the environmental monitoring is given in Clause 7 where reference to other relevant ISO documents is also made and guidance to assess the uncertainty to dose assessment result is given in Clause 11.

6 Assessing and monitoring human exposure

For a representative assessment of the dose in order to highlight the possible effects on human health, an analysis of the exposure routes is a prerequisite. For this purpose, the current and planned use of the environment of the site is included in the assessment, as it defines which exposure pathways to the representative individual are relevant. If a new use is planned, a renewed assessment should be carried out. Realistic, average or worst-case scenario exposures can be defined and depending on the purpose of the exposure assessment, the data needed for the assessment differ depending of the scenario chosen.

Even when representative individuals are not directly exposed to direct radiation, exposure assessments need to consider the various ways by which indirect exposure might occur, and their significance, see Figure 2.

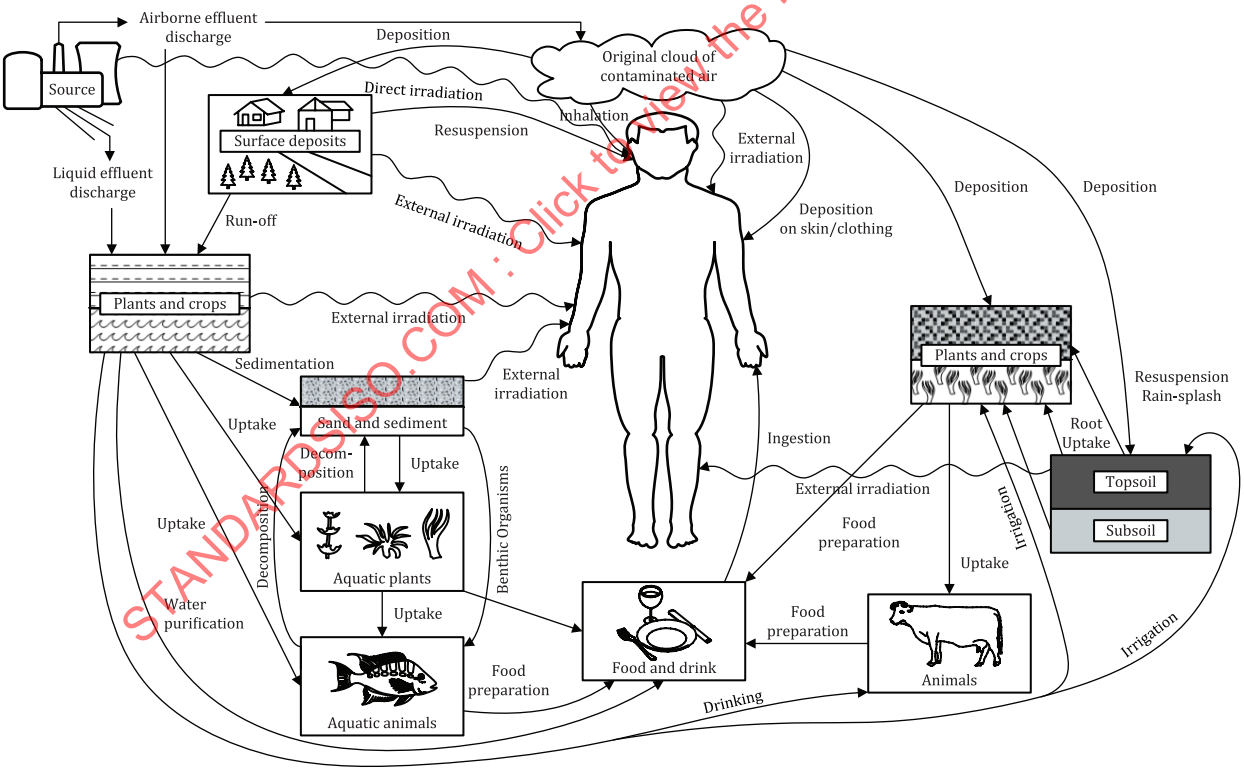

Figure 2 — Possible pathways of exposure for members of the public as a result of discharges of radioactive material to the environment[9]

Two main categories of exposure pathway are defined: external exposure pathway when the source of exposure remains outside the body and internal exposure pathways when the source of exposure is incorporated into the body. The importance of the various exposure pathways depends on:

a) The radiological properties of the material released (e.g. gamma emitters, beta emitters or alpha emitters; physical half-life);

b) The physical (e.g. gas, liquid or solid) and chemical (e.g. organic or inorganic form, oxidation state, speciation, etc.) properties of the material and its migration characteristics;

c) The dispersal mechanism and factors affecting it (e.g. stack height, meteorological conditions, etc.) and environmental characteristics (e.g. climate, type of biota, agricultural production, etc.);

d) The locations, ages, diets and habits of the exposed individuals or population.

e) The radionuclide is different in its behaviour in the environment and health impact on humans depending on its chemical form or compound. The health risk depends on both the activity concentration of a radionuclide and the duration and the route of exposure (skin contact, inhalation, ingestion, etc.). For this reason, analysis of the changes that the radionuclide undergoes as a result of these transformations and phase transfer processes prior to exposure is an important part of exposure assessment.

To identify the media that have to be sampled and tested for their activity concentration, it is important that the appropriate sampling strategy and measurement can be applied to assess the dose to an individual.

Thus the assessment of the annual effective dose $E(t_1)$ for a year t_1 to a representative individual requires the quantification of the contributions due to external exposure E_{ext} and the internal exposure due to ingestion and inhalation of radionuclides, E_{ing} and E_{inh} respectively. According to ICRP publications[3] such an evaluation has to be performed for the different tissues, T, taking into account the age dependence of exposure and of dose factors and the tissue weighing factors, w_T, see Formula 1:

$$E(t_1)=E_{ext}+E_{ing}+E_{inh}=\sum_T w_T\cdot\left(H_{T,ext}+H_{T,ing}+H_{T,inh}\right) \quad (1)$$

One important purpose of environmental monitoring is to provide the data that permit the analysis and the evaluation of the three terms of the formula to compute the human radiation exposure: $E_{ext}, E_{ing}, E_{inh}$.

Thus, the quality of the environmental input data that characterize the parameters of the mathematical formulae used to compute the effective dose are essential.

For this purpose, programs for monitoring radionuclides in the environment focus on pathways of human exposure, see Table 1. An exposure pathway defines routes from a source of radionuclides and/or radiation to a target: a representative person or a population through the different environmental media.

Monitoring programs of the environment usually integrate the sampling of plant or animal species that are not part of the diet of the exposed individuals or population. They are selected for their ability to accumulate radionuclides at higher activity concentrations than those usually found in the atmosphere, soil or water compartment where they live. These bioindicators are considered as "sentinel" organisms to detect minor radioactivity level variations of their environment. For example, mosses and lichens are common bioindicators included in atmospheric monitoring program and brown algae and mussels are used for the monitoring of seawater radioactivity. Their sampling and measurement is beyond the scope of this document.

Table 1 — Assessment of the effective dose by various pathway

Pathway of human exposure	Quantity monitored	Symbols
External exposure	Dose rate in air as a function of time and space or external dose measured with personal dosimeter	E_{ext}
Internal exposure (inhalation)	Activity concentration in air as a function of time and space	E_{inh}
Internal exposure (ingestion)	Activity concentration of water, food (including milk) as a function of time and space	E_{ing}

Monitoring for the purpose of radiation protection of the public can be divided into three categories: source monitoring, environmental monitoring, and individual monitoring[9], see Figure 3. Environmental monitoring provides good information in the event of an accident or for variations from normal situations. Environmental monitoring can be used to detect changes in long-term trends in activity concentrations or dose rates in the environment.

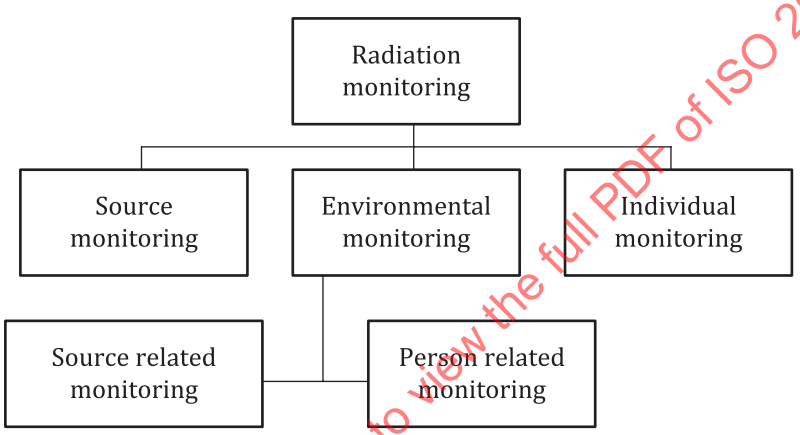

Figure 3 — Types of monitoring for radiation protection of the public[9]

Environmental monitoring can be further subdivided into two categories: source-related and person-related monitoring. Source monitoring involves monitoring a particular source or the discharges from a nuclear installation or other practice in which radioactive materials are used. The quantities measured are usually dose rates and activity concentrations of environmental samples at predetermined location at a site and/or discharge rates.

Person-related monitoring is used when there may be several sources irradiating the same representative person/population. The main objective is to assess the doses deriving from all these sources[9].

7 Environmental monitoring program

7.1 General

According to the scope, for planned and existing exposure situations, the purposes of radioactivity measurements of environmental matrices and food is to assess the radiological impact on the population and establish the environmental status around a facility. Supplementary objectives of the monitoring program for planned and existing exposure situations are the following:

— routine surveillance of the impact on the environment of the radioactivity released from nuclear installations or of the general evolution of the radioactivity in a region;

— characterization of radioactivity in the environment for research;

— planning and surveillance of remedial action;

— investigations of the long-term consequences of nuclear or radiological emergencies.

Consequently, radioactivity measurements of the different matrices are performed in a variety of situations, but a generic approach can be described, with the following three main steps:

— planning process: depending upon the objective, a sampling strategy is defined that leads to the definition of a sampling plan;

— sampling process: the resulting sampling operation in the field leads to sorted samples that are packed and transported to the laboratory;

— testing laboratory process: the preparation of test samples for laboratory measurement.

The laboratory in charge of sampling should have a documented sampling plan with sampling procedures. The sampling plan should be available at the location where the sampling is undertaken (see ISO/IEC 17025).

7.2 Planning process

7.2.1 Selection of the sampling strategy

The selection of the sampling strategy depends on the main objectives and on the results of the initial investigation of selected areas of a site. The sampling strategy should lead to the knowledge of the nature, activity concentration, spatial distribution, as well as temporal evolution, of the radionuclides, considering changes caused by migration, atmospheric conditions and land/soil use.

The design of an environmental monitoring program needs to consider factors such as: meteorological conditions (variations in wind direction and strength, rain, etc.), current and future land use, agricultural practices, soil and hydrological properties.

In addition, relevant diet, and age distribution of the local population should be considered in the vicinity of the installation.

An initial investigation of the area should be carried out to validate the sampling strategy.

7.2.2 Description of the sampling plan

The sampling plan should be developed according to the objectives of the monitoring. It should specify the selection of sampling areas and units, the sampling pattern, the sampling points, the types of samples, the sampling procedures and equipment, as well as the safety requirements for the personnel.

Details, such as the selection of sampling areas and the sampling units that result from the type of grid applied to these areas, are given in the following clauses and in Annex A.

7.3 Sampling process

7.3.1 Collection of samples

The collection of any samples in the field should conform to the established sampling plan in accordance with the objectives of the monitoring to be done.

A single sample or increments are collected from each of the selected sampling units.

Depending of the types of matrices to sample, details are given in Annex B.

7.3.2 Preparation of the sorted sample

The preparation of sorted samples is carried out by reduction of single or composite samples. A sorted sample should be representative of the average value of one or more given matrix characteristics. The identification, labelling, packaging and transport procedures of sorted samples to the laboratory should guarantee the preservation of their characteristics.

Details are given in Annex B.

7.4 Laboratory process

7.4.1 Handling of the laboratory sample

After arrival at the laboratory, the samples are considered as laboratory samples for storage and further pre-treatment before their analysis.

Details are given in Clause 10 and Annex B.

7.4.2 Preparation of the test sample

In most cases, the measurement of the sample activity is performed on a sample that is subject to pre-treatment in the laboratory, unless otherwise requested by the users of the measurement results. This pre-treatment, according to ISO 18589-2[10], shall be done to obtain a test sample whose physical-chemical characteristics (after drying, crushing, sieving and homogenizing) are constant over time for all radioactivity analyses to which the sample might be submitted, thus rendering the results easier to interpret (see ISO 11464[11]). Following this first pre-treatment step, certain radionuclide measurements require a homogenization and volume reduction by ashing, leaching or dissolution to obtain the test sample.

Details are given in Annex B.

If some material is stored for future investigations or for the purpose of settling a potential dispute, subsamples should be taken from the laboratory sample or the test sample in an acceptable and documented manner.

8 Environmental monitoring to assess external exposure

8.1 General

The main external exposure pathways to consider are direct exposure from:

— radionuclides in the atmosphere, due to the radionuclide dispersion of the authorized discharges from the installation;

— radionuclides deposited on the soil surface or on sediments (on the shores of rivers, lakes or the sea) or building surfaces (walls, roofs and floors) or vegetation (trees, bushes and grass).

Thus, the annual external effective dose $E_{ext}\ (t_1)$ during the year, t, in Sv, is assessed knowing the external exposure of airborne radionuclides in air $E_{ext,\,air}\ (t_1)$ and deposited on soil surface $E_{ext,\,soil}\ (t_1)$, following Formula 2:

$$E_{ext}\left(t_1\right)=E_{ext,\,air}\left(t_1\right)+E_{ext,\,soil}\left(t_1\right) \tag{2}$$

In specific cases, such as when radionuclides are deposited onto the skin, contact exposure should be assessed, but it is beyond the scope of this document.

Figure C.1 gives an example of investigation steps to identify the cause of increase of ambient dose rate above the background level.

8.2 Direct measurement of the external dose

When the direct estimation of the ambient dose equivalent rate H^* is measured, the external exposure to radiation due to β and γ emitter radionuclides and, when needed, neutron radiation are computed using the following Formula 3, $\dot{H}^*(10)$ is used as an estimator for E:

$$E(t_1) = \dot{H}^*(10) \tag{3}$$

Thus, the evaluation of dose due to the external exposure linked to the radioactive discharges from nuclear facilities, the knowledge of the ambient dose rate $\dot{H}^*(10)$ as a function of time, t, at different locations in the environment of the installations, see Table 2.

Different devices can be used for the direct estimation of the ambient dose equivalent rate $\dot{H}^*(10)$. They typically measure the photon spectrum and identify the gamma emitting radionuclide. The devices installed on site are usually operating continuously. They are also designed to measure the ambient dose equivalent (rate) due to neutron radiation in fields that contain neutrons usually with energies below 20 MeV.

Passive devices such as TLD (Thermo-Luminescence Dosimeter), OSL (Optically Stimulated Luminescence) Dosimeter or Glass RPL (Radio-Photo Luminescence) Dosimeter are used for over time integrated measurement. These are dosimetry systems that measure external photon and/or beta radiation in the dose range between 0,01 mSv and 10 Sv.

Table 2 — Suggested frequencies of sampling and measurement for discharges of radionuclides to the environment

Monitored constituents [$H^*(10)$]	Frequency
Gamma dose rate	Continuously
Gamma dose integrated	Twice a year
Neutron dose rate (if neutron radiation is foreseen)	Continuously
Neutron integrated rate (if neutron radiation is foreseen)	Twice a year

The following ambient radiation monitoring types can be selected:

— Monitoring station: outdoor measurement device for direct continuous monitoring of $H^*(10)$ that can be supplemented by an aerosol sampler, cartridges to collect iodine and noble gas, bubbling samplers for tritium and carbon-14, a rainwater collector. This equipment provides different samples that are measured in a measuring laboratory. Meteorological parameters measurement apparatus are often jointly installed in this type of station.

— Monitoring post: field measurement equipment with a continuous monitoring of $H^*(10)$;

— Monitoring point: outdoor measurement equipment with passive integrating dosimeter;

— Continuous measurement of ambient radiation dose rate (gamma dose rate monitors without photon spectrum, such as semiconductor, Geiger-Müller and proportional counters)

Short time variations of $H^*(10)$ can be estimated through continuous measurements of the ambient radiation dose rate at monitoring posts and stations. These measurements are used for the early detection of an increase of the ambient dose level, and using meteorological data, to localize the source of the event.

The selection of integrating dosimeters for measuring the cumulative dose by gamma rays should take into account their sensitivity, accessibility and fading.

The contribution of natural background radiation to the dose equivalent shall be known to assess the contribution of low dose equivalents or low dose equivalent rates of a nuclear installation. The natural contribution is usually assessed using several dosimeters, considered as background dosimeters, that are measuring $H^*(10)$ at representative posts and/or points that are never under the radioactive dispersion plume of the atmospheric discharges of the installation. The average background value indicated by these background dosimeters is subtracted from the measurement result of the dosimeters installed under the influence of the discharges of the installation. The background monitoring points are placed on a location where site contribution is improbable (e.g. contribution of buildings, condition of ground surface, wind direction, variability of cosmic ray).

Typically, detection limit of these dosimeters is 0,2 mGy after subtracting the background contribution for a measurement period of 12 months.

8.3 Indirect assessment of the external dose

8.3.1 External exposure from contaminated soil

To assess the annual external exposure from contaminated soil $E_{\text{ext, soil}}$ of Formula 2, the mathematical formulae assumes a semi-infinite source region with a uniform activity concentration, $C_r(t)$, in soil surface of a radionuclide, r, at time, t, then the external dose equivalent H_T in tissue, T, can be expressed as given by Formulae (4) and (5):

$$H_{T,\text{ext,soil}}(t_0+1) = h_{T,r} \cdot \int_{t_0}^{t_0+1} C_r(t)\,\mathrm{d}t \tag{4}$$

$$H_{T,\text{ext,soil}}(t_0+1) = \sum_i H_{T,\text{ext,soil}}(t_0+1) \tag{5}$$

where h_T is the time-independent conversion coefficient for external exposure[12]. When the time integration ranges from t_0 to t_0+1 year, with t_0 the year of interest, H_T represents the dose associated to tissue, T, with a single year of exposure.

For fresh fallout C_r is in Bq·m^{-2} and $h_{T,r}$ the tissue dose equivalent coefficient for organ or tissue T (Sv·Bq^{-1} s·m^{-2}), i.e., the dose equivalent per unit time-integrated exposure to a radionuclide r. For long term deposit of contamination in soil C_r is in Bq kg^{-1} and $h_{T,r}$ the tissue dose equivalent coefficient for organ or tissue T (Sv Bq^{-1} s kg^{-1}), i.e., the dose equivalent per unit time-integrated exposure to a radionuclide r. This means that $h_{T,r}$ is contamination depth dependent.

As radionuclides released into the environment can persist in soil, the dose associated with a practice/facility is assessed considering the time integral of the deposit over many years based on the annual atmospheric discharges of a facility.

Different parts of two standards can be used to assess the activity concentration evolution of radionuclides in soil, $C_r(t)$, ISO 18400 series[13]to[25] for the sampling stage and ISO 18589 series [10][26]to[31] for the radioactivity measurement stage.

When designing sampling programs for the purpose of soil monitoring and characterization, identification of sources and effects of pollution of soil and related materials, the general principles are given in ISO 18400-101[14], ISO 18400-104[17], ISO 18400-107[20], ISO 18400-102[15] and ISO 18400-103[16]. The following parts deal with various aspects of sampling for the purposes of soil investigation, including different types of soils, natural, agricultural (ISO 18400-205[25]), urban and industrial (ISO 18400-203[23]). ISO 18400- 204[24] deals with soil gas sampling.

The seven parts of ISO 18589 [10][26]to[31] are applicable for the purpose of radiation protection as they describe the radioactivity monitoring of soil in the following situations:

— initial characterization of radioactivity in the environment;

— routine survey of the impact of nuclear installations or of the evolution of the general territory;

— investigations of accident and incident situations;

— planning and surveillance of remedial action;

— decommissioning of installations or clearance of materials.

8.3.2 External exposure from contaminated air

Radionuclides authorized to be released in the atmosphere and thus dispersed in the environment can cause an external exposure as well an internal exposure by inhalation during the immersion of the representative person/population in the dispersion plume.

Considering the annual external exposure from contaminated air, $E_{\text{ext, air}}$, of Formula 2, the effective dose from external exposure due to an immersion in contaminated air $H_{T,\text{ext,air}}$ can be assessed using the following Formula (6):

$$H_{T,\text{ext,air}} = t \cdot \sum_i CF(r) \cdot C_r \tag{6}$$

where t is the exposure duration, $CF(r)$ is the conversion factor for radionuclide r obtained from IAEA[32] and C_r is the average concentration of radionuclide r, in air, expressed in $\text{Bq}\cdot\text{m}^{-3}$ during the exposure duration and estimated using the data obtained from the radioactivity monitoring program of the atmosphere.

The atmospheric radioactivity C_r is monitored by different stations on site that can be equipped with aerosol sampler, iodine and noble gas cartridge, bubbling samplers for tritium and carbon-14, rainwater collector and meteorological measurement.

9 Environmental monitoring to assess internal exposure

9.1 General

The main internal exposure pathways to consider are:

— inhalation of radionuclides, in the form of gases and/or aerosols in a plume (see above clause);

— inhalation of resuspended radionuclides initially deposited on soil or sediment surface, or natural radionuclides;

— ingestion of food or beverages that contain radionuclides, which have been discharged into the atmosphere or water body and their transfer from soil or sediment to the vegetation and animal agricultural products (meat, milk, eggs or marine food).

The inhalation route, following resuspension of particles, is difficult to quantify because there are 4 to 5 orders of magnitude uncertainty about the value of the resuspension rate applied to the concentration of the soil surface layer in order to estimate the atmospheric concentration induced by the resuspension of soil particles. Moreover, in normal situations, this pathway is negligible in respect of direct exposure by radionuclide inhalation from the dispersion plume.

Figure C.2 gives an example of investigation steps to identify the cause of increase of activity concentration of environmental samples above their background levels.

9.2 Inhalation

The committed effective dose due to the inhalation of r radionuclides during a year from t_0 to t_0+1 is given by

$$E_{\text{inh}}(t_0+1)=\dot{V}\cdot\sum_r \bar{A}_r(t_0+1)g_{\text{inh},r} \tag{7}$$

where $A_r(t_1)$ is the activity concentration of the radionuclide, r, in air during year, t_1, expressed in Bq·m^{-3} estimated using data obtained from a radioactivity monitoring program of the atmosphere.

Age dependent committed effective dose coefficients for inhalation $g_{\text{inh},r}$ are estimated using models of radionuclide behaviour and radiation absorption in the body expressed in Sv·Bq^{-1}, and have been derived and regularly published by ICRP.

Depending on the monitoring situation (effluent discharges, resuspension etc.), the variation during year, t, of the activity concentration of the radionuclide, r, of the aerosols and/or in gaseous form in the atmosphere should be measured in the atmosphere to properly assess $A_r(t)$.

Depending on the radionuclides, the committed equivalent dose in tissue or organ T is then given by:

$$H_{\text{inh},T}(t_0+1)=\dot{V}\cdot\sum_r \bar{A}_r(t_0+1).g_{\text{inh},r,T} \tag{8}$$

where

$H_{\text{inh},T}(t_1)$ age dependent committed equivalent dose in tissue or organ, T, due to the inhalation of air during a year, t_1;

$g_{\text{inh},r,T}$ dose coefficient for the equivalent dose due to inhalation of radionuclide, r.

ISO 10473[33] describes a method for the measurement of the mass of particulate matter in ambient air and is based on the absorption of beta rays by particulate matter.

The activity concentration in ambient air at all locations or regions is variable with time due to meteorological conditions, topography and patterns of emissions. When not continuous, the atmospheric monitoring shall be performed over a long interval of time to ensure that a sufficiently wide range of conditions is covered. In this case, ISO 9359[34] gives an efficient sampling method for the assessment of annual ambient air radioactivity $A_r(t)$.

Data uncertainty can be quantified based on the GUM and ISO 11222[35] that provides a method for the quantification of the uncertainty of a time average of a set of air quality data obtained at a specified location over a defined averaging time strata. ISO 20988[36] provides guidance and specific statistical procedures for uncertainty estimation in air quality measurements including measurements of ambient air, stationary source emissions, indoor air, workplace atmospheres and meteorology. In line with the fit for purpose approach, ISO 14956[37] provides the evaluation of the suitability of a measurement procedure by comparison with a required measurement uncertainty.

^{222}Rn is considered the main source of human exposure to natural radiation, as radon is estimated to contribute up to 52 % of the total natural internal dose (UNSCEAR[1], WHO[8]). The radon activity concentrations in air sampled above continental areas vary over five orders of magnitude, between a few Becquerels per cubic metre and several thousand Becquerels per cubic metre in very confined spaces, such as caves. The radon activity concentration, as well as the potential alpha energy concentration of its decay products, varies tremendously during the daytime, from day to day, and over seasons. This variability shall be known when extrapolating the value of A_r(t) from measurement results obtained for shorter periods of measurement time.

Thus, environmental assessment studies are regularly commissioned to assess the radon exposure of the public that had justified the publication of IEC and ISO standards on equipment and test methods to estimate radon activity concentration (IEC 61577 series [38]to[41] and ISO 11665 series[42] to [48]). The

4 parts of IEC 61577 deal with measuring instruments as well as Systems for Test Atmospheres with Radon (acronym STAR) and radon decay products.

IEC 61577-1[38] covers the general characteristics of tests and calibrations of radon and radon decay products measuring instruments as well as general characteristics of radon and radon decay products measuring instruments. IEC 61577-2[39] deals with the specific requirements for radon measuring instruments. IEC 61577-3[40] presents the specific requirements for radon decay product measuring instruments and IEC 61577-4 [41] concerns the STAR needed for testing, in a reference atmosphere and the instruments measuring radon.

To supplement IEC 61577 series, the ISO 11665 series, presents the approach to select the sampling method, duration and sampling season that should be compatible with the intended use of the data including their associated uncertainty. Depending on the duration of the sampling phase, three types of measurement methods (ISO 11665-1[42]) are distinguished

— a spot measurement method that gives indications, at the scale of a few minutes at a given point, of the radon activity concentration or the potential alpha energy concentration of short-lived radon decay products in open and confined atmospheres (ISO 11665-3[44] and ISO 11665-6[47]);

— a continuous measurement method that allows the assessment of temporal changes in radon activity concentration in the environment (ISO 11665-5[46]);

— an integrated measurement method that gives indications of the average activity concentration of 222Rn or of the average potential alpha energy concentration of short-lived radon decay products in the air over periods varying from a few days to 1 year (ISO 11665-2[43] and ISO 11665-4[45]).

ISO 11665-7[48] gives guidelines to characterize the release of radon in the atmosphere, estimating the ^{222}Rn surface exhalation rate (of soil, rock, building interface, wall) in the environment during onsite investigations such as the search of radon sources or comparative studies of exhalation rate on the same site.

9.3 Ingestion

9.3.1 General

The internal exposure due to ingestion during a year t_1 is given by

$$E_{\text{ing}}(t_1) = E_{\text{ing},w}(t_1) + E_{\text{ing},f}(t_1) \tag{9}$$

where

$E_{\text{ing,w}}(t_1)$ age dependent committed effective dose due to consumption of water during the year, t_1 in Sv;

$E_{\text{ing},f}(t_1)$ age dependent committed effective dose due to consumption of food during the year, t_1 in Sv.

Thus, to assess the internal exposure, the monitoring program shall cover the drinking water and food that can be ingested by a representative person, infant and adult.

9.3.2 Ingestion of water

ISO 5667-1[49] sets out the general principles for, and provides guidance on, the design of sampling programs and sampling techniques for all aspects of the sampling of water.

ISO 5667-5 [50] establishes principles to be applied to the techniques of sampling water intended for human consumption and ISO 5667-21[51] those to be applied to the techniques of sampling water provided for drinking and for use in the manufacture of food and beverage products.

ISO 5667-3[52] presents guidance on the preservation and handling of water samples.

ISO 5667-20[53] provides guidance on the use of sampling data for decision-making and their compliance with thresholds and classification systems.

9.3.3 Ingestion of agricultural products

Agricultural products, such as rice, wheat, corn, vegetables, tea, grass and feedstuff for cattle; are another important pathway. Especially, grass samples are useful for dose assessment from the milk produced by dairy animals.

Among ISO standards that give guidance on food sampling those on agricultural food products (ISO 7002:1986[54]), milk and milk products (ISO 707[55]; ISO 5538[56]), cereals and cereal products (ISO 24333[57]), fresh fruits and vegetables (ISO 874[58]), oilseeds (ISO 542[59]), oilseed residues (ISO 5500[60]), microbiology of the food chain (ISO 17604[61]), tea (ISO 1839[62]), and animal feeding stuffs (ISO 6497[63]; ISO 6498[64]) may be mentioned.

Sampling strategy according to the objective for evaluating dose assessment is described in Annex A.

Table 3 — Examples of typical sample and frequency of sample collection to assess the internal exposure

Monitored constituents	Frequency	Remarks
Aerosol	Continuous	Dust monitor
	Quarterly	Low volume air sampler
Ground and surface water	Quarterly	e.g. Tap water, river water, well water
Milk	Quarterly or each month when dairy animals are on pasture	
Soil	6 months or yearly	Surface soil
Agricultural products	At harvest season	Vegetables, fruits, meat etc.
Index plants	Quarterly or yearly	
Atmospheric deposition (fallout)	Monthly	
Seawater	6 months	Surface water
Sediment in the sea	6 months or yearly	Surface sediment

10 Radioactivity measurement

10.1 General

As specified in ISO/IEC 17025, the laboratory should use test methods, including sampling procedures, which meet the needs of the customer. Thus, the standards on sampling mentioned in the following subclauses are used by testing laboratories in charge of the sampling step of the radioactivity monitoring of soil, water and foodstuff.

10.2 Soil

Using the following parts of ISO 18589 gives measurement results of C_r, expressed in Bq kg^{-1} of dried soil sample, needed for example in Formula 4 to assess the external exposure from contaminated soil.

ISO 18589-1[26] gives the general guidelines and definitions and ISO 18589-2[10] provides guidance for the selection of the sampling strategy, sampling and pre-treatment of samples.

ISO 18589-3[27] specifies the identification and the measurement of the activity in soils of a large number of gamma-emitting radionuclides using gamma spectrometry (photon energy between 5 keV and 3 MeV). ISO 18589-4[28] describes a method for measuring ^{238}Pu and its 239+240 isotopes in soil

by alpha spectrometry samples using chemical separation techniques, ISO 18589-5[29] describes the principles for the measurement of the activity of ^{90}Sr in equilibrium with ^{90}Y, and ^{89}Sr using different chemical separation methods and a proportional counter (PC) or a liquid scintillation counter (LSC) and ISO 18589-6[30] provides a method that allows an estimation of gross radioactivity of alpha- and beta emitters present in soil samples.

ISO 18589-7[31] specifies the identification of radionuclides and the measurement of their activity in soil for mapping using in situ gamma spectrometry with portable systems equipped with germanium or scintillation detectors. This document is used by those in charge of baseline study of the radioelements that needs to be conducted at any site where human activity has the potential to change the levels of radioactivity in the environment as recommended by IAEA (2010).

10.3 Water

The annual internal dose in an organ or a tissue T due to ingestion of radionuclides present in drinking water is given by

$$E_{T,\mathrm{ing,w}}(t_1) = \sum_r E_{T,\mathrm{ing},r,\mathrm{w}}(t_1) = \sum_r \sum_{t=0}^{t_1} C_r^{\mathrm{w}}(t) * U_{\mathrm{w}}(t) * \int_{t_0}^{t_1} \frac{\partial g_{\mathrm{ing},r,T}}{\partial t} \mathrm{d}t \tag{10}$$

$C_r^{\mathrm{w}}(t)$ is the time dependent activity concentration (Bq·kg^{-1}) in drinking water of a radionuclide, r, during year t_1, that can be estimated using the data obtained by a monitoring program of drinking water radioactivity. $U_{\mathrm{w}}(t)$ is the time dependent consumption of drinking water (kg).

A large set of ISO standards, e.g. ISO 9696[65], ISO 9697 [66], ISO 9698[67], ISO 10704 [68], ISO 13160[69], ISO 13161[70], ISO 13162[71], on test methods can be used to obtain $C_r^{\mathrm{w}}(t_1)$ from monitoring waters sample. These standards cover laboratory test methods, in situ and on-line measurements, of any individual radionuclide of natural or artificial origin, as well as radionuclide nonspecific parameters such as gross alpha activity and gross beta activity.

These standards on test methods form the basis for the monitoring of drinking water in line with the approach recommended by WHO since the first edition of its guidelines published in 1984. Thus, four standards are commonly used for the determination of tritium activity concentration using a liquid scintillation counting method (ISO 9698[61]), for the measurement of gross alpha activity (ISO 9696[65]), gross beta activity (ISO 9697[66]) and on gamma-ray spectrometry (ISO 10703[72]), respectively. The latter is related to IEC 61452[67] that establishes methods for the calibration and use of germanium spectrometers for the measurement of gamma-ray energies and emission rates and the calculation of source activities from these measurements.

Two alternative test methods to determine the gross alpha and gross beta activities are published with a new sample preparation stage by direct evaporation to dryness described in ISO 10704[68] and with a different type of measuring equipment by liquid scintillation counting detailed in ISO 11704[74].

Several standards on test methods for specific man-made radionuclides in water can be used in the monitoring program. Test methods refer to ISO 13160[69] for ^{90}Sr; ISO 13162[71] for ^{14}C; ISO 13168[75]) for ^{3}H and ^{14}C; and ISO 13167[76] for plutonium, americium, curium and neptunium measurements. To supplement this latest standard and, as mass spectrometry techniques are now in common use in testing laboratories, a test method standard for plutonium and neptunium using ICP/MS (ISO 20899[77]) is also published.

Naturally occurring radionuclides belonging to the U and Th series present in drinking water usually give radiation doses higher than those due to man-made radionuclides at activity concentration characteristic of planned or existing situations. Thus, a set of supplementary standards should be available for testing laboratories on test methods for uranium isotopes, ^{226}Ra, ^{222}Rn, ^{210}Pb and ^{210}Po.

A test method of uranium isotopes using alpha spectrometry is described in ISO 13166[78] and a method using liquid scintillation in ISO 13169[79]. ISO 17294-2[80] on the application of inductively coupled plasma spectrometry (ICP-MS) includes a normative annex on the determination of uranium isotopes.

ISO 13165, a standard on test methods for ^{226}Ra, is published in 3 parts. ISO 13165-1[81] proposes using liquid scintillation counting, ISO 13165-2[82] using emanometry and ISO 13165-3[83] co-precipitation followed by gamma spectrometry. Concerning ^{210}Po, a test method by alpha-particle spectrometry is presented in ISO 13161[70] and for ^{210}Pb a test method using liquid scintillation counting in ISO 13163[84].

Guidance on radon in drinking-water supplies provided by WHO[8] suggests that controls should be implemented if the radon of drinking-water for public water supplies exceeds 100 Bq l^{-1}. To follow this recommendation, ISO 13164 series on the measurement of ^{222}Rn, which is divided in 4 parts, can be used. ISO 13164-1[85] gives general guidelines for sampling, packaging, and transporting of all kinds of water samples, for the measurement of the activity concentration of ^{222}Rn. ISO 13164-2[86] specifies a test method for the determination of ^{222}Rn activity concentration through the measurement of its short-lived decay products by direct gamma spectrometry of a water test sample. ISO 13164-3[87] describes a rapid test method (less than 1 h) for the determination of ^{222}Rn activity concentration following its transfer from the aqueous phase to the air phase by degassing and its quantification using emanometry. ISO 13164-4[88] describes a test method for the determination of ^{222}Rn activity concentration in waters by two phase extraction and liquid scintillation counting.

10.4 Food stuffs

The annual internal dose due to ingestion of radionuclides present in food is given by

$$E_{T,\mathrm{ing,f}}(t_1)=\sum_r E_{T,\mathrm{ing},r,\mathrm{f}}(t_1)=\sum_r\sum_{t=0}^{t_1} C_r^{\mathrm{f}}(t)*U_{\mathrm{f}}(t)*\int_{t_0}^{t_1}\frac{\partial g_{\mathrm{ing},r,T}}{\partial t}\,\mathrm{d}t \tag{11}$$

$C_r^{\mathrm{f}}(t)$ is the time dependent activity concentration (Bq·kg^{-1}) in food stuffs of a radionuclide, r, during year t_1, that can be estimated using the data obtained by a monitoring program of food stuffs radioactivity. $U_{\mathrm{f}}(t)$ is the time dependent consumption of food stuffs (kg).

Portable instruments intended for operation under field conditions can be used for measuring the specific activity of beta-emitting radionuclides in food/foodstuffs (IEC 61562[89]) as well as gamma emitting radionuclides (IEC 61563[90])

In laboratory conditions, the determination of gamma emitting radionuclides in food sample, C_r^{f}, using high resolution spectrometry can be performed following ISO 20042[91] requirements. Consideration shall be given to ensuring homogeneity of the test sample, avoiding cross-contamination, optimising the sample geometry for gamma ray spectrometry, minimising the loss of activity (for example, of volatile radionuclides) and the shelf life required. Objects in the sample which could cause heterogeneity shall be removed and residues shall be measured separately, if necessary. The preparation technique may also depend on the sample size available.

Solid samples may be measured as supplied, dried or ashed. Oven-drying and freeze-drying, fractionation and comminution can be used.

Some ISO standards give guidance for the preparation of dried and ashed test sample of cereals and cereal products (ISO 2171[92]), fresh fruits and vegetables (ISO 1026[93]; ISO 763[94]), oilseeds (ISO 664[95]), oilseed residues (ISO 749 [96]), tea (ISO 1572[97]; ISO 1575[98]), meat and meat products (ISO 936 [99]), and animal feeding stuffs (ISO 5984 [100]).

The determination of beta emitters activity concentration in food, C_r^{f}, in liquid (aqueous or organic) and solid states can be determined using the test method by liquid scintillation counting described in ISO 19361: 2017[101].

The determination of alpha emitters activities in food in liquid and solid states, C_r^{f}, can be determined using the generic test method by alpha spectrometry (ISO 20045 in preparation).

For food under a liquid state, standards used for radioactivity measurement of water samples can be adapted. For solid food, the different parts of ISO 18589[10][26]to[31] can be used.

11 Variability and uncertainty

Carrying out an uncertainty/variability analysis of the dose assessment model is one of the important first steps when using "best estimates" selected from a set of measurement results of the parameter values.

As with any measurements, monitoring data have associated uncertainties that arise from technical uncertainties, the non-representativeness of samples and/or measurements, and human errors. These uncertainties should be reduced as far as possible by means of quality assurance procedures.

The computation of the uncertainty budget of the dose-assessment process can be performed following the methods described in IAEA Safety Standards[102].

Performing a sensitivity analysis identifies the input parameters of the dose assessment model which have the greatest influence on the dose results, and thus requiring the lowest uncertainties.

Uncertainty attached to the monitoring results, as well as the variability of the parameters of the dose assessment model, should be considered in the interpretation of monitoring data and dose assessment results. Thus, the quantification of the uncertainty/variability of the monitoring data is an important source of supplementary information to provide to regulatory bodies, see Table 4.

Table 4 — Major sources of uncertainties in dose assessment made on the basis of data from environmental and individual monitoring modified from IAEA[102]

Pathway of human exposure	Quantity monitored	Source of uncertainties in dose assessment
External exposure	Dose rate in air as a function of time and space	Location and duration of stay of people in the area monitored (climate, time, season etc.)
	External dose measured with personal dosimeter	If the dosimeter is worn continuously, the dosimeter has little uncertainty.
Internal exposure (inhalation)	Activity concentration in air	Location of people, inhalation rate, dose coefficient, age, gender
Internal exposure (ingestion)	Activity concentration of water, soil, food and milk as function of time and space	Age dependent consumption rate of food and other media, origin of food, seasonal variation, time spent and location of individuals (soil ingestion), kinds of nuclides

For many cases, the uncertainty linked to the activity concentration results of the test samples is small compared to uncertainties in sampling the environmental matrices, water or food. Even in such cases, an estimate of the uncertainty of the measurement is conducted, so that it can be demonstrated that the measurement results are fit for purpose.

The uncertainty in the measurement results shall be estimated and documented in accordance with the requirements of ISO/IEC Guide 98-3. In accordance with ISO/IEC 17025, the major components of uncertainty shall be estimated, including the one attached to the sampling stage; for high accuracy measurements, the uncertainty budget shall be evaluated in even greater detail.

Use of measured activity concentrations taken from appropriate media, for example activity concentration in foods at the point of consumption, allows for a better estimate of dose compared to those quantities being solely estimated using models[103]. However, when most measurement results are below detection limits, the dose assessment, where the limit of detection is assumed to be the actual activity concentration, does not give a realistic assessment of doses as it overestimates the actual dose.

12 Quality assurance and quality control program

Quality control operations shall meet the requirements of ISO/IEC 17025. The influencing variables affecting each measurement result are discussed in the relevant ISO/IEC standards and shall be taken into account by a testing laboratory in charge of the environmental and food radioactivity monitoring.

Care shall be taken in order to limit as much as possible the influence of parameters that may bias any measurement and lead to overestimated or underestimated dose assessment results.

It is also recommended that testing laboratories participate in national or international proficiency test exercises. For in situ measurements, verification exercises are organized by national or international organisations.

A quality assurance plan shall be established, describing the actions to ensure that measurement results reported meet the customer's specification, in accordance with ISO/IEC 17025.

The quality assurance plan shall include:

— periodic quality checks;

— verification/test measurements;

— staff training and assessment;

— documentation of results from quality control checks.

The frequency of the checks shall be based on results from the validation studies and historical records.

A training plan and periodic assessment shall be established for personnel who plan and carry out measurements including sampling, perform data analysis and prepare reports.

It is recommended that staff carrying out in situ measurements, follow specialist courses on the measurement techniques and participate in measurement campaigns organized by experts, educational establishments, equipment manufacturers or software producers.

Records of the results of all quality control checks and dates shall be retained. Any discrepancies and corrective actions taken shall also be recorded.

Annex A
(informative)

Example of sampling procedures for environmental and food matrices

Matrices	Sample part or form	Sample size	Sampling method
Aerosol and gas samples	Filter papers	Sample size should be determined depending on purpose of the method (total β radioactivity measurements, radiochemical analysis, γ-ray spectrometry, Solid State Nuclear Track Detectors, SSNTD). Usually it is 0,1 m^3/min for one week and (0,2 to 1,0) m^3/ min from a few hours up to 24 h.	Low and/or high-volume air samplers
Fallout		Monthly sampling	Sampling tub is placed 1 m above ground level.
Water		For total β: about 2 l Radiochemical analysis: 20 l to 100 l (usually 10 l) γ-ray spectrometry: 40 l to 60 l	Polyethylene bucket or dipper
Soil	Collected from the surface layer and also from the first sub-layer, depending on purpose. Soil sample should be collected under 20 cm depth from the surface.	At least (2-3) kg fresh soil	Soil sampler (inner diameter (5 to 8) cm, height 20 cm)
Agricultural products (include cereals, vegetables, tea)	Edible or feed parts	About (5 to10) kg in raw weight	The pasture is cut 10 cm above the ground
Animal (milk)	Raw milk from a cow, market milk and dry milk	Sample amount is about 5 kg, milk powder (1 to 2) kg	Milk sample is squeezed from cow. Market milk and dry milk are purchased from factory or shop of the same production lot.
Food	Daily foods are collected from one person (adult) in a day.	The daily foods should be collected on normal day	Duplicate portion study

Annex B
(informative)

Example of sample preparation methods for environmental and food matrices

Matrices	Sample preparation procedure
Aerosol and gas samples	Air sampler High and/or low volume air sampler is used depending on the purpose. An activated carbon cartridge can be installed for collecting iodine. Filter paper Glass fiber and cellulose filter paper with collection efficiencies of 95 % or greater are usually used, depending on the purpose. For radiochemical analysis, an ordinary chemical analysis grade filter paper may be used. Location of sampling Choose wide and flat sampling locations. Sampling height is more than 1 m above the ground level. Filter paper is ashed during preparation.
Water (river, lake, well, tap)	River and lake water Surface water is collected. Well and tap water Flush out pipe a few minutes before taking the sample.
Soil	A number of samples are collected from various points in agricultural fields. However, number of sample points can be slightly reduced if soil conditions are well known from previous research. In uncultivated land, select a location with long-term collection. Collected soil samples are dried, ground and passed through a sieve.
Plants (grass)	Ashing procedure is applied to samples during preparation. After cooling, the ash sample is ground and passed through a sieve.
Food (milk, vegetables, agricultural products)	Ashing procedure is applied to the edible parts of samples during preparation. After cooling, ash sample is ground and passed through a sieve.